JBA consulting

Water Resource Benefits of Working With Natural Processes

Final Report

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This report describes work commissioned by Sean Arnott, on behalf of the Environment Agency, by an email dated October 2019. The Environment Agency's representative for the contract was Sean Arnott. Iain Craigen, Emily Christopherson, Abigail Speakman, Joseph Cherry, Alexander Jones, Susan Wagstaff and Barry Hankin of JBA Consulting carried out this work.

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Purpose

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Carbon Footprint

JBA is aiming to reduce its per capita carbon emissions.

Executive summary

This project has sought to improve understanding of how Working With Natural Processes (WWNP) may provide water resource benefits alongside flood risk reduction and other multiple benefits.

As part of the 2017 Abstraction Plan, there is a stronger catchment focus and shift to sustainable abstraction as well as need to meet Abstraction Reform. WWNP has been gaining momentum for its potential to restore natural processes and provide flood risk management, biodiversity and water quality benefits. However, harnessing the power of nature to benefit water resources is an approach that has not gained significant traction in the UK to date.

This project has undertaken a literature review focusing on the function WWNP may have in both benefiting or dis-benefiting water resources, to inform consideration of potential measures. Several key themes were identified including the roles of vegetation, soils and storage as well as the site-specific nature of soils and geology limiting the transfer of evidence to other areas. The review identified that vegetation density can have a strong influence on water budgets with dense woodland limiting the proportion of water made available for potential recharge. However, younger or lower density woodland or smaller vegetation canopies and root-depth provided evidence of potential water resource benefit suggesting guidance is necessary to manage this effectively. Enhanced storage of surface water through a wide-range of WWNP interventions through a catchment were investigated. These features were found to provide benefits to water resources where sited over permeable geology but also provide opportunity to attenuate flows for potential recharge further downstream together with a suite of multiple benefits. A wide-range of soil management practices which could be integrated as WWNP were noted to potentially help reduce water losses (whether that be evaporative or as surface runoff), improve soil infiltration and increase the water available for recharging water resources. The key findings from the literature review were summarised within a WWNP matrix.

To consider the interactions between WWNP and groundwater processes, the project investigated Areas of Interest within ten Priority Catchments (PCs) including site visits and engagement with local groundwater specialists. These typically comprised areas where more collaborative water management is required or have significant abstraction demands or challenges. Conceptual models for areas within these Priority Catchments were completed, covering a range of geologies, land covers, land management practices, water demands, challenges and climates to review the potential for WWNP to improve water resources and maximise multiple benefits.

Based on findings from the research, data review and conceptual understanding, a GIS assessment was undertaken to identify the aquifer recharge potential across each AoI as well as identify a suite of WWNP measures. These GIS deliverables can be used as a screening approach to identify WWNP potential and gain an indicative understanding of their recharge and multiple benefit potential with respect to their location in the catchment. The GIS approach developed is scalable, so prioritisation of water resource beneficial measures could be applied nationally with further consideration of weighting different layers, using Open Data and handling soil, geology and topographic combinations that have not been encountered in the PCs.

The project recommends that future work on WWNP uses an integrated water and catchment management approach, keeping water resource benefits in mind and ensuring these remain balanced with flood risk management requirements going forward. Application of continued groundwater modelling is recommended to upscale WWNP and provide quantifiable predictions for their potential benefit to water resources. Further evidence is sought to support future funding opportunities and ensure water resource challenges are managed effectively and sustainably.

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Abbreviations

AEP	Annual Exceedance Probability
Ag-MAR	Agricultural Managed Aquifer Recharge
AoI	Area of Interest
BFI	Baseflow Index
BGS	British Geological Survey
CEH	Centre of Ecology and Hydrology
DEM	Digital Elevation Model
DWSZ	Drinking Water Safeguard Zones
DTM	Digital Terrain Model
ELJ	Engineered Log-Jam
ET	Evapotranspiration
GIS	Geographic Information Systems
HER	Hydrologically Effective Rainfall
HYPE	Hydrological Predictions for the Environment
IFRM	Integrated Flood Risk Management
JBA	Jeremy Benn Associates
LiDAR	Light Detection And Ranging
LWD	Large Woody Debris
MAR	Managed Aquifer Recharge
NBS	Nature Based Solutions
NERC	National Environment Research Council
NFM	Natural Flood Management
PC	Priority Catchment
RAF	Runoff Attenuation Feature
SAC	Special Area of Conservation
SBC	Scottish Borders Council
SCS	Soil Conservation Service
SEPA	Scottish Environment Protection Agency
SMD	Soil Moisture Deficit
SRST	Stubble-Retained Subsurface Tilled Fallow
SUDS	Sustainable Urban Drainage Systems
WFD	Water Framework Directive
WWNP	Working With Natural Processes
WWNP CS	WWNP Mid/Upper-Catchment Storage Potential
WWNP FZ	WWNP Lower Catchment Floodplain Zone Potential
WWNP FROP	WWNP Lower Catchment Floodplain Reconnection Potential
WWNP LCM	WWNP Arable and Grassland Land Cover Management Potential
WWNP SPS	WWNP Slowly Permeable Soils Potential
WWNP RAF	WWNP Runoff Attenuation Features Potential
WWNP RZ	WWNP Mid/Upper-Catchment Riparian Zone Potential

Glossary

Annual exceedance probability - the probability of a flood of a particular magnitude, or greater, occurring in any given year.

Gaining watercourse – a waterbody which has increasing flow with distance downstream due to discharge of groundwater baseflow into the surface watercourse.

Flood Zone 2 – an Environment Agency dataset predicting areas of land assessed as having between a 1 in 100 and 1 in 1,000 annual probability of river flooding (1% – 0.1%), or between a 1 in 200 and 1 in 1,000 annual probability of sea flooding (0.5% – 0.1%) in any year.

Losing watercourse – a waterbody which has decreasing flow with distance downstream due to leakage of flow from the surface watercourse to the ground. Watercourses may be both gaining and losing at different times and locations.

1 Introduction

1.1 Aims and objectives

This report aims to assess the water resource benefits of Working With Natural Processes (WWNP) and make recommendations for measures that are potentially more favourable for increasing recharge. The assessment has been informed by literature and data reviews, site visits and working with experts from ten Priority Catchments, shown in Figure 1-1, that were put forward as part of the Abstraction Reform.

The project focusses on WWNP measures that should improve water resources through a range of measures to: increase soil infiltration rates; groundwater recharge rates; aquifer storage and summer baseflows across Areas of Interest (AoI) defined within ten PCs (Figure 1-2). These have been prioritised in order of the Abstraction Reform (see below), commencing with four PCs of the Idle & Torne, South Forty-Foot, Cam & Ely Ouse, East Suffolk, which commenced in 2018-19, followed by six further PCs that commenced a year or more later: the Alt & Crossens, Arun & Western streams, Brue, Otter, Till & Tweed and Wye.

WWNP involves restoring, or emulating, the natural function of catchments, rivers, floodplain and coasts. On rivers, it can include: restoring rivers and floodplains; creating wetlands; capturing runoff in the uplands and in low-lying ponds; and planting (or removing) trees, depending upon their type, location and density. Many WWNP measures promote infiltration (and groundwater recharge), help store water and slow down the rate at which it enters river systems. During this work, we will be focusing on the WWNP measures that provide most benefits to water resources whilst realising other multiple benefits where possible.

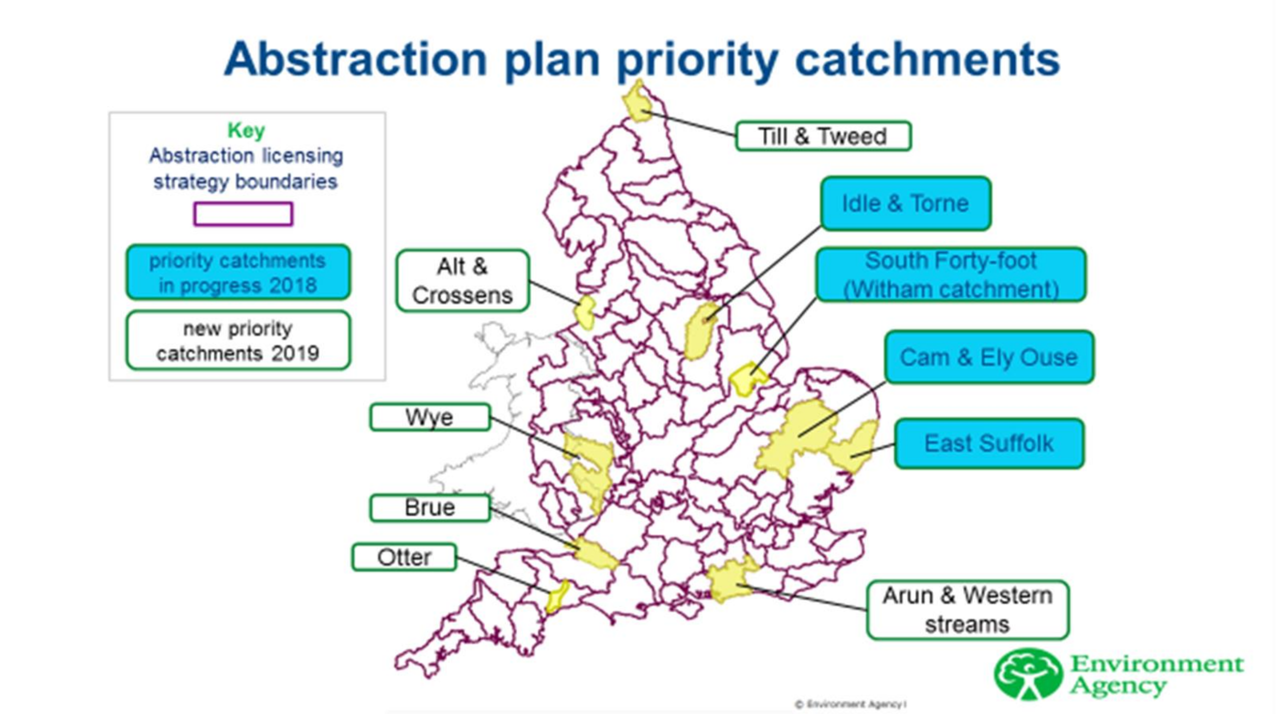

Figure 1-1: Overview of the 10 Priority Catchments (PCs)

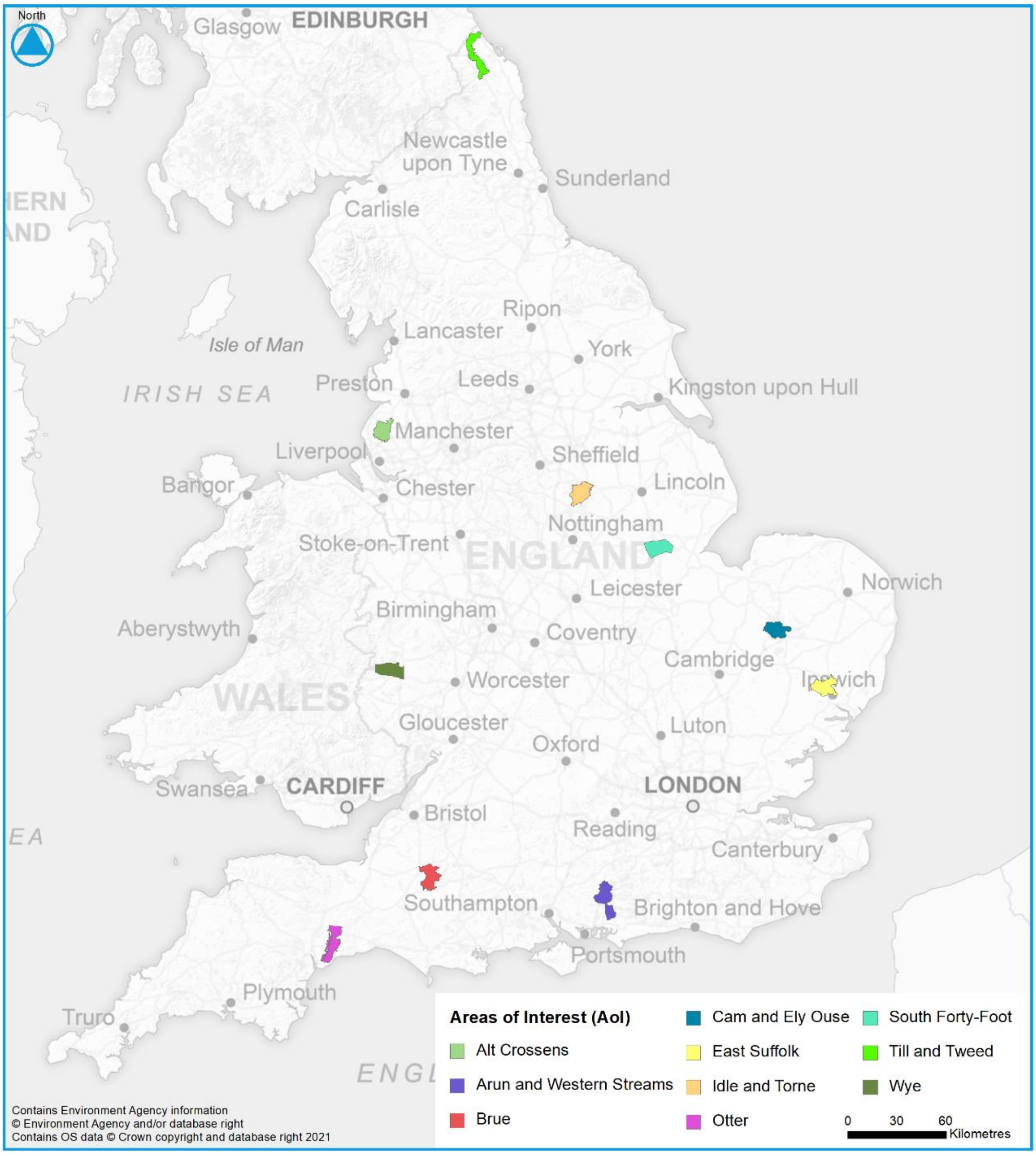

Figure 1-2: Priority Catchment Areas of Interest (AoI)

1.2 Background

The main project driver is to embed the concept of groundwater benefits of WWNP into the catchment approach and apply this to all catchment licensing strategies by 2027 as stated in the new Abstraction Plan[1], but the outputs will also help the Environment Agency to deliver on a range of themes from the Defra 25-year plan to meeting requirements of the Water Framework Directive (WFD) or River Basin Planning. Furthermore, the Environment Agency have set out future national water resource needs (2020[2]) based on current practices including a need to resource a further 3,435 million litres per day (Ml/d) nationally by 2050 and improve resilience within a rapidly changing environment. The Abstraction Plan was published in December 2017, which sets out how the Environment Agency aims to reform abstraction by:

- Making full use of existing regulatory powers and approaches to address unsustainable abstraction,
- Developing a stronger catchment focus – bringing together the Environment Agency, abstractors and catchment groups to develop local solutions to existing pressures and to prepare for the future. These local solutions will:
    - Protect the environment by changing licences to better reflect water availability in catchments and reduce the impact of abstraction,
    - Improve access to water by introducing more flexible conditions that support water storage, water trading and efficient use,
- Supporting these reforms by modernising the abstraction service, making sure all significant abstraction is regulated and bringing regulations in line with other environmental permitting regimes.

Ten Priority Catchments (PCs) were selected to develop and test innovative solutions to achieve greater access to water and address unsustainable abstraction. PCs have been chosen where there:

- Is unmet demand for water and/or there are concerns that abstraction is damaging the ecology,
- Is potential for water to be shared amongst abstractors,
- Are a number of abstractors who we can work with to trial new and innovative ways of managing water abstraction.

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1 https://www.gov.uk/government/publications/water-abstraction-plan-2017

2 https://www.gov.uk/government/publications/meeting-our-future-water-needs-a-national-framework-for-water-resources

1.3 Report Structure

The following outlines the location for each stage of the project and will be available either within this report or its accompanying appendices.

Section 2 - Literature review and WWNP matrix

Section 3 - Data review

Section 4 - Generic conceptualisations

Sections 5-14 - Catchment-specific conceptualisation and WWNP potential key summaries. Each catchment has a standalone report which includes a significant amount of additional local conceptual, site visit and WWNP understanding as provided in Appendix C. Each catchment has GIS layers supplied with an ArcGIS project for indicating WWNP potential areas as supplied in Appendix D.

Section 15 – WWNP potential area definition and attribution

Section 16 – Project summary and recommendations

Appendix A – WWNP summary matrix

Appendix B – JBA groundwater flood map summary

Appendix C – Priority Catchment conceptual model reports

Appendix D – WWNP and wider recharge area GIS deliverables

2 Literature Review

2.1 Introduction

Nature Based Solutions (NBS), Natural Flood Management (NFM) or Working with Natural Processes (WWNP) cover a wide spectrum of measures aiming to restore, or emulate, natural processes to reduce flood risk. The recent Environment Agency Evidence Base (Burgess-Gamble *et al*., 2018) summarises the state of evidence for flood risk reduction for a range of such measures, whilst also summarising multiple benefits they could also deliver using a 'benefit wheel' approach. This aligns with growing recognition of the importance of taking an integrated flood risk management (IFRM) approach (Aid and International Development Forum, 2014, WWF, 2016, Bridges *et al*., 2018). IFRM seeks to understand the whole system, and for example recognises there are trade-offs to be made between making catchments more resilient to the extremes of flooding and drought. An immediate implication for this research on understanding the water resources benefits of WWNP is that we need to be more subtle in the targeting of different types of measures in different places and consider the sub-surface flows through soils and geology more than previously. Some general conceptualisations for better integrated approaches include the use of ponds on permeable soils above aquifers, that enhance temporary storage of flood waters and then drain down enhancing recharge, whilst making more storage available for a subsequent flooding (see Hankin *et al*., 2018). For areas of depleted aquifer recharge, the integrated approach might also mean *avoiding* measures such as planting of dense, or coniferous, woodland. Meanwhile, prioritising the use of leaky barriers and floodplain reconnection to reduce flood risk and promote capture of high flows into areas where potential local recharge rates are considered to be elevated on the basis of high soil permeability and appropriate hydrogeology.

2.2 Woodland Creation

When considering the water resource benefits of tree-planting, there is a trade-off between the generally beneficial increases in infiltration rates and generally detrimental increased interception and evapotranspiration which can reduce water yield into groundwater stores. It is important to distinguish between different types and configurations of planting, including riparian, wider woodland or shelterbelts (planting within narrow corridors), and how woodland is managed and/or drained long-term. The majority of research described here infers that wider, denser planting of trees can result in a net reduction of recharge on an annual basis compared with grassland. The extent of this is species-specific and less dense planting of broadleaved woodland, with leafless periods, has generally been found to tip the balance to net benefits of increased infiltration over interception.

Kowsar (2005) showed that within a dryland environment where evaporation rates are significant, the average infiltration rate of a treeless system was 3.8cm/h compared to 9.3cm/h in an afforested system. However, more locally in the Pontbren catchment, Wales, infiltration rates were measured to be 60% higher under young native woodland shelterbelts compared to adjacent heavily grazed pasture (Bird *et al.,* 2003). However, the soils in this catchment are thin which could have influenced the measured high infiltration rates and the shelterbelts will likely have inherently reduced the potential for livestock soil compaction. Furthermore, the geology **and soils exert a strong influence on the effectiveness of trees as a risk reduction strategy and cannot be reliably transposed to other catchments of differing character.**

Alternative sources show that trees can reduce transpiration losses compared to other land cover on specific soils through their biological and physical processes. For example, drainage into the ground (recharge) under beech woodland under a cretaceous chalk catchment was found to be 17% higher than under grassland in the same catchment, this effect was determined to be caused by higher transpiration rates of grass on chalk soils, sustained by capillary rise in these soils. In comparison, under sandy soils at Clipstone, Nottinghamshire, drainage into the ground (recharge) under beech and ash was found to be 17% to 25% higher than under grassland (Calder *et al.,* 2002). Whilst, oak on sandy soils overlying the Sherwood Sandstone aquifer may locally reduce recharge by 14-32% when compared with grassland (Calder *et al.,* 2002). Kedziora (2015) noted that whilst evapotranspiration losses increased directly over shelterbelts, their capability to shelter adjacent fields resulted in a reduction in evapotranspiration over the adjacent arable land.

The sensitivity of recharge to vegetation cover was studied at Clipstone, Nottinghamshire where it was found that evapotranspiration losses of water from the sandy soils was consistently greater under oak than grassland (Calder *et al.,* 2008). Drainage under oak was estimated to be 260mm less than grass over a four-year period, inferring that oak woodland cover would negatively impact groundwater resources (Calder *et al.,* 2002). Meanwhile, drainage into the ground from the 2-9m zone below ground (recharge) under Corsican pine was estimated to be 612mm less than grassland over the same four-year period, demonstrating the potential adverse effect of conifer woodland on potential groundwater recharge relative to grassland. The fact that interception and transpiration rates are also higher in trees (23% in oak at Clipstone), compared to grassland will also contribute to reductions in water budget reaching the ground surface.

In contrast, in Sherwood Forest, Nottinghamshire, recharge rates in juvenile broadleaved trees were shown to exhibit 3 to 4 times more annual average recharge than mature broadleaved trees, suggesting that trees have an effect of increasing recharge where the tree canopy is young because there is less canopy storage and less direct re-evaporation of water from all the above ground tree surfaces (Carbo *et al*., ND). To support this research, McCulloh and Robinson (1993) found that water usage from trees are greater than those of crops. Further implying that a greater water loss occurs in mature vegetation because of a larger, denser, more complete canopy and longer roots which extend to greater depths within the soil.

Research has been found to show that planting density has a strong influence on whether trees are beneficial or detrimental to water resources. At a moderate planting density, it is thought that the intermediate infiltration rate and intermediate evapotranspiration rate, counterbalance to optimise groundwater recharge (WeForest, 2016). The findings from a modelling study by Ilstedt *et al.* (2006) led to the conclusion that **moderate planting is the optimum density to enhance groundwater recharge, because this ensures that water losses through interception and evapotranspiration do not exceed infiltration.** The study by Ilstedt *et al*. (2006) assumed ‘moderate planting’ consisted of an average of 20 trees/ha over a 100ha site with an average tree size of a 67 square-metre canopy area. Therefore, contrary to other research which implies woodland creation is a dis-benefit to groundwater recharge, this research suggests it can improve groundwater resources under the right planting density.

Research by George *et al.* (2019) based on 80 surveyed sites in Western Australia concluded that in groundwater recharge areas, water tables were only significantly impacted where planting covered over 70% of the catchment area. Furthermore, in groundwater discharge areas, the impact of tree planting with respect to the water table remained highly localised (10-30m) to planted areas.

Tree maturity is important in influencing recharge as well as plantation density. Conifer afforestation was implemented in the Coalburn catchment, England, to assess the impact of afforestation on upland water supplies. After 5 years, 90% of the

150ha catchment had been afforested. The results showed a progressive increase in water use by trees, reduced peak flows, a 200mm/year reduction in water yield in the catchment and baseflow (annual BFI) declined (Robinson, 2015). Furthermore, the modelling of the catchment estimated a reduction in return period from 1 in 13 years to 1 in 20 years. However, peaks flows increased by 20% in the first 5 years after afforestation due to the drainage and ditching operations pre-planting, although after 20 years, peak flows reduced by 5% (O'Connell *et al*., 2004). This research suggests that as trees become increasingly mature, their ability to intercept and restrict water from reaching the ground for recharge increases, although this also leads to reducing surface runoff and peak flows.

Across the literature, conifers were consistently identified as the species that reduce recharge rates the most with their all year round tree canopy coverage as a dominating factor. **Nisbet *et al.* (2011) recommended that conifer woodland should be avoided in areas of low water availability.** To support this, another study showed that a 10% increase in conifer plantations in the catchment were associated with a 40mm decrease in water yield. **In comparison, for a 10% increase in broadleaved woodland, a lesser decrease in water yield of 25mm was found (Bosch and Hewlett, 1982)**. Additionally, in the Coalburn catchment, coniferous woodland was found to intercept 25-45% of annual rainfall in the UK in comparison to 10-25% for the case of broadleaved woodland (Calder *et al.,* 2002). However, these impacts are likely to be more substantial where large-scale planting occurs and therefore conversion to broadleaf woodland is likely to be less of an issue at small-scale plantations (Nisbet *et al.,* 2011a).

Carbo *et al*. (ND), state that wood pasture contributes to the highest average annual recharge, this is 45% more than broadleaved woodland and 52% more than conifers, supporting other findings that conifers are the most unsuitable forestry for benefits to groundwater recharge. In contrast, recharge was 1.3-2.5% greater under grass than beech and ash woodland on a chalk site in Hampshire and 1.4% greater in grassland underlain by clay, for every 10% of the catchment covered by woodland (Harding *et al*., 1992). These studies demonstrate how the tree species planted can strongly control recharge rates and water yields.

High evapotranspiration rates in woodland areas will also reduce the amount of effective rainfall that enters the subsurface and is available for groundwater recharge. A study comparing the recharge and evapotranspiration rates between oak and heath found that oak provided approximately 50% of the recharge capability compared to heath (390mm for oak and 733mm for heath) (Ladekarl *et al.,* 2005). Furthermore, although heath monitored higher soil evaporation (316mm for oak and 205mm for heath), once transpiration was accounted for, oak monitored higher combined water losses than heath. Therefore, this study concurs with other research that shorter rooted vegetation has greater recharge to benefit groundwater resources.

Riparian woodland (planting within land immediately adjoining a watercourse or standing water) can potentially be a beneficial intervention to water resources. Riparian woodland has the ability to maintain low flows as it has the effect of increasing overland flow retention and soil infiltration and can also slow flows (Burgess-Gamble *et al*., 2018). However, it is important to consider the type of vegetation planted, because trees such as willow have high water use, and subsequently could further reduce low flows (Nisbet *et al*., 2011b), although this can create additional below-ground storage capacity to store drainage losses (Burgess-Gamble *et al*., 2018). Floodplain woodland can provide additional benefits to water quality, through reducing diffuse pollution and enhancing sediment deposition (Jeffries *et al.,* 2003). Trees are also effective in removing nitrates and phosphates and fixing toxic metals, and thus improving water quality (Gambrell, 2014). Ellis et al*.* (1994) found that riparian vegetation systems can intercept sediment and pollutants and are particularly beneficial in urban areas for accumulating stormwater pollution. Furthermore, riparian vegetation is effective at enhancing sediment deposition in the riparian zone and reduce downstream siltation (Piėgay and Bravard, 1996). In the River Thur in Switzerland, riparian vegetation along a section of the river removed approximately 20% of nitrates and the aquifer in the restored section had greater nitrate removal than in the channelised section (Peter *et al*., 2012), demonstrating how riparian vegetation can strengthen denitrification processes.

The nature of overlying soil causes trees to have a different biological effect on infiltration (Eldridge and Freudenberger, 2005). For example, on fine-textured soils, infiltration and sorptivity (ability to absorb, or desorb liquid) were greater under trees compared to that on grass slopes and cultivated land. A positive correlation between higher nutrient concentrations and a shorter distance to tree trunks was also found. Trees have been found to be beneficial in immobilising contaminants and reducing the potential for leaching of contaminants into ground and surface water through uptake and fixation in their woody biomass (Nisbet *et al*., 2011a).

Further research has looked at the influence of tree species planted on certain soil types and geologies. **A modelling study on the Sherwood Sandstone aquifer in Nottinghamshire, UK, found a 45% reduction in annual recharge as a result of an increase in oak woodland cover in the borehole capture zones which are used for public water supply (Zhang and Hiscock, 2010).** Where partial conversion from arable land to woodland was evident in the model, groundwater recharge reductions were approximately 30% (Zhang and Hiscock, 2010). The study concluded that recharge values estimated for the two borehole capture zones are dependent on type and proportion of crop cover. **Where oak and grassland were overlying sand, recharge was 16-48% greater over the grass.** This was thought to be because oak can sustain higher transpiration rates on drought prone sandy soils because it has deeper roots than grass (Zhang and Hiscock, 2010).

Increased infiltration under trees has also been correlated with increased soil nutrient concentrations. In wooded and savanna ecosystems globally, elevated concentrations of carbon, nitrogen and extractable potassium, phosphorus and calcium were found in soils below trees compared to adjacent open grassland (Eldridge and Freudenberger, 2005). Conversely, trees may impact groundwater quality due to enhanced nitrification and acidification (particularly with conifers) caused by sifting of atmospheric pollutants under canopies and deposition of acidic leaf litter (Allen and Chapman, 2001). Trees have been found to scavenge atmospheric pollutants two to three times more effectively than short vegetation. However, scavenging rates vary depending on the tree species, for example, conifers scavenge more effectively than broadleaf species because of their greater aerodynamic roughness (Allen and Chapman, 2001). Therefore, this implies that water quality beneath conifer woodland especially can potentially by impacted by acidification and nitrification.

2.3 Large Woody Debris and Leaky Barriers

Tree trunks can be effective for Natural Flood Management (NFM) and water resources when used in channel in addition to being planted within the catchment. Where tree trunks are placed perpendicular to the flow direction arranged as wooden dams, this has typically been termed leaky barriers, with the intention that more water is attenuated in periods of high flows and diverted onto the floodplain for additional storage, attenuation and availability for groundwater recharge. Where tree trunks are placed in an along stream direction or randomly in the channel, this had been called large woody debris, and sometimes engineered log jams (Addy and Wilkinson, 2016).

Leaky barriers in streams creates a backwater effect that increases local water levels particularly in small magnitude flow events; however, during higher magnitude events, backwater rise can increase to the point where the storage provided by leaky barriers is reduced (Geertsema *et al*., 2017). **Where local water levels increase and are forced out of bank and onto the floodplain, there is potential for storage, attenuation and availability for groundwater recharge.** However, this process can only directly benefit local recharge if the floodplain is underlain by more permeable soils and geology (Acreman *et al.,* 2003).

There are wider benefits to implementing this measure, for example, if local trees are cut down and used for log jams in streams, this results in more sunlight being able to reach the forest floor and growth of shorter vegetation and shrubs with reduced water demand. Short *et al.* (2018) supported the findings of this research that if wood used for leaky barriers are sourced from coppiced local woodland, increased availability of light reaching the woodland surface resulted in increased plant diversity and shrubs at these levels. Since shorter rooted plants enhance groundwater recharge, **deforestation of trees and the successional growth of smaller shrubs will benefit water resources, whilst the logs can be used to further benefit NFM and water resources nearby (Broadmeadow *et al*., 2014)**.

Altered flow regimes caused by freshwater storage also modifies chemical and nutrient cycling in river systems. **These pond-dam complexes created by leaky barriers act as sediment traps which store sediments and nutrients and in-turn improve downstream water quality, thereby helping to achieve WFD guidelines (Janes *et al*., 2017)**. For example, increased storage of carbon in ponds acts as a net store for carbon and provides greater benefits for climate mitigation (Puttock *et al.,* 2017). In lower order streams, debris dams have accounted for up to 87% of sediment storage in freshwater systems (Puttock *et al.*, 2017). Shading provided by wood reduces local water temperatures, this effect is associated with downwelling which is induced by wood whereby surface water is forced down into the sediment where it interacts with groundwater (Sawyer & Cardenas, 2012; Grabowski *et al*., 2019). This temperature moderation effect is enhanced where riparian trees on the floodplain provide additional shading and benefits to fish and other aquatic organisms.

Furthermore, leaky barriers improve hydrological connectivity between the river and floodplain and this increased wetness alters biogeochemical cycling of nutrients and creates new habitats. Woody debris also provides essential shelter and habitat for fish during high flow events (Grabowski *et al*., 2019). On the other hand, during low flows this can cause a restriction to fish passage through the large woody debris if not properly installed and managed. Fish passage may also become restricted if the density of materials used is sufficiently high to block with sediment potentially worsening the ecological quality of the waterbody downstream (Kiraly *et al*., 2015).

The construction of leaky barriers should consider which material is used and where it is implemented. For example, weak wood such as birch is affected by decomposition and thus will have a shorter lifespan than hardwoods such as oak, ash or chestnut (Environment Agency, 2019). Research (Hankin *et al*., 2020) has modelled the likelihood of woody debris cascade dam failure depending on its location within the drainage network. The findings showed that dams on the main watercourse, i.e. within the base of a valley, are associated with an increased risk of cascade failure whereas dams located on side-branches or tributary channels predicted a reduced potential of cascade failure. This was assumed to relate to the increased connectivity of downstream channels which were more susceptible to any surges from dam failures higher in the network, prompting a higher rate of cascade failure. Recent guidance (Environment Agency, 2019) provides further recommendations for construction of large woody debris dams including guidance on their setting, width, height and fixing to reduce the likelihood and magnitude of negative impacts occurring.

Woody debris can be implemented in lower energy streams to reduce risks of mobilisation and associated blockage. Chalk streams are lower in energy and there is a lower risk of mobility, and the dam would be less likely to breach and therefore the potential risk to infrastructure downstream is reduced. As a result, there is a growing confidence to implement large woody debris in chalk streams. The National River Restoration Inventory (NRRI) database states that 63% of woody debris projects have been undertaken on sedimentary geology with a third of these on chalk (Cashman *et al*., 2019).

Leaky barriers and woody debris dams can additionally be used for Enhanced Hillslope Storage (EHS). EHS is commonly used as a NFM measure to retain overland flow to improve hillslope storage capacity (Metcalfe *et al.,* 2018). A hydrodynamic modelling study was undertaken using TUFLOW to simulate a potential very large hillslope pond where a 9% reduction in flows were achieved through diverting flows into a single pond with a capacity of 27,000 cubic metres (Metcalfe *et al.,* 2017), but this notably exceeds the current threshold of 25,000 cubic metres, for which the Reservoir Act applies. From a water resource benefit perspective, it is important to consider where these features are located in relation to porous medium that provides the pathway for recharge. They may provide opportunity for direct recharge over more permeable geologies or where sited on less permeable geologies may still slow surface runoff for recharge further downstream within a system of varying geology and permeability.

Leaky barriers can have a significant benefit to water quality. Sediment retention upstream improves water quality downstream by reducing nitrate and phosphate levels; wood dams are also successful in retaining and breaking down organic matter in the river (Acuna *et al*., 2013). In Blackbrook, St. Helens in Merseyside, four log jams, implemented in 2012, reduced average phosphorus concentrations by 3.6mg per litre, and by 2035 it is predicted that 792 cubic-meters of sediment will be stored in ponds retained by the log jams (Burgess-Gamble *et al*., 2018). Cost-benefits of this study found that the cost of four log jams were approximately £2,000 and expected benefits are £4,500, demonstrating predicted benefits are more than double the costs (Burgess-Gamble *et al*., 2018).

2.4 Rewilding

Rewilding is the large-scale restoration of ecosystems and natural processes where nature can sustain itself. Rewilding can improve infiltration through reintroducing and enhancing natural processes in the environment. For example, sheep grazing is one of the main upland land practices in the UK, however overgrazing compacts the soil and reduces infiltration capacity. Therefore, by reducing the stocking density of sheep on upland slopes and instead introducing low to medium-density planting could increase infiltration by up to 67 times (Carver, 2016). Multiple benefits include an increased species richness and colonisation of new species (Torres *et al*., 2018).

Rewilding in the Scottish Highlands changed two ecosystem services (aesthetics and timber biomass). It was found that rewilding increased woody biomass and restored natural tree processes after 15-years and improved the aesthetic quality of the area, concluding that rewilding can be used for ecosystem recovery in moorland landscapes (Ermgassen *et al*., 2018).

Another form of rewilding is altering farmland practices to restore the natural hydrological regime through dam or dyke removal. This removes infrastructure which previously fragmented freshwater habitats and allows the natural hydrological regime to be resumed which benefits the ecological quality of the river (Torres *et al*., 2018).

Beaver reintroduction is another measure of enhancing natural processes to benefit water resource management. In the River Otter, beavers were introduced into a 3ha fenced area within the watercourse. Since introduction of beavers in 2016, beavers have constructed thirteen dams consisting of woody material and each storing up to a depth of 1m of additional water within ponds. As a result, peak flows leaving the site during storm events have reduced by an average of 30% and a significant and constant baseflow has been maintained at the site, **demonstrating how beaver developed leaky barriers can be beneficial for water resources, NFM and habitat creation (Puttock *et al.*, 2017).** However, engineered large woody debris, particularly when following recent guidance (Environment Agency, 2019) is likely to be a more robust intervention than beaver dams. On a significantly larger scale than typical UK watercourses, structural failure of beaver dams have been reported to result in flood outbursts and responsible for loss of human life (Butler and Malanson, 2005).

Beavers have been found to be effective in restoring habitats and reintroducing ecosystems in Eastern Scotland. Following 12 years of beaver presence in an area of degraded agriculture, species richness had increased by 46% per plot, on average, and the cumulative number of species increased by 148% (Law *et al*., 2017). The beaver introduction transformed degraded agricultural land into a heterogeneous wetland environment and provided benefits for water and sediment storage leading to flow attenuation. Tree felling by the beavers decreased tree canopy cover which reduced water uptake from the ground and subsequently increased soil moisture waterlogging the ground to produce a wetland environment (Law *et al.,* 2017). Therefore, rewilding via beaver introduction may be beneficial to modifying ecosystems to benefit water resources. Furthermore, beavers have recently been introduced to Spains Hall Estate in Finchingfield, Essex, although the aim of the scheme is to reduce flood risk, a wetland has also been created with the aim for it to slowly release water in drier periods to benefit water resources (GOV.UK, 2018).

Furthermore, if large woody debris is not properly managed there is potential for blockage. For example, culvert blockage would raise the water level upstream and may result in a flood wave and associated debris overtopping the dam and creating hazards downstream, which would not have occurred if no dams were installed (Hankin *et al*., 2020). There is a further risk that if a dam upstream collapses then this may cause other dams further downstream to collapse in a cascade, increasing the hazard downstream. This risk is therefore an important consideration in planning and installation of large woody debris.

Nature Recovery Network is a potential solution to improve natural systems including wildlife habitats. Natural England's Nature Networks Evidence Handbook (Crick *et al*., 2020) highlights the fundamental need for restoring natural hydrological pathways, the role WWNP can provide and the need for a decision-making framework that adapts with scale of intervention. The creation of a network involves protecting wildlife sites on a local scale, connecting them to one another through creating ponds, hedges, small woods and meadows as examples to enable wildlife to move freely through the landscape. To achieve this, habitats would be created between local wildlife sites and would strengthen their network and connectivity. Creating ponds would provide greater water storage capacity to benefit water resources, slow flows and provide habitat to improve biodiversity. A study of nature recovery potential was undertaken by Lincolnshire Wildlife Trust (Wildlife Trust, 2018) where they demonstrated the nature recovery potential of road verges. 150 miles of road verges were protected, which amounted to 200 hectares of wildflower-rich grassland, increasing biodiversity.

2.5 Runoff Attenuation Features, Offline Storage, Wetlands and Washlands

Offline storage areas and washlands can reduce the conveyance of flows downstream and enhance the long-term supply of water. **Washlands can recharge aquifers during flooding and retain water at subsurface levels during low-flow periods, which can predominantly occur during summer (Brunet *et al.*, 2003)**. Runoff Attenuation Features (RAFs) provide water storage in times of drought and promote infiltration and groundwater recharge. An example of offline storage features is in the Belford catchment, Northumberland where 35 RAF features (5 as offline ponds) created approximately 8,000 cubic metres of floodwater storage (Quinn *et al.,* 2013) and has since been further expanded in feature numbers to a volume of 12,000 cubic metres storage.

In the River Adour in France, storage attenuation features were studied to investigate their role in regulating aquifer recharge. It was found during low water periods in summer, the sub-surface storage is estimated to be 4,200,000m^3, which is 67% of the total available storage (Brunet *et al.,* 2003). The lower water table in summer, increases storage capacity in the event of flooding, and during a flood the water table rises to the surface and saturates the floodplain. In the Adour catchment the aquifer is close to the surface and can be recharged by both sub-surface and surface water including during a flood. **Thus, there are benefits to both water resources, and flood peak attenuation**. However, over-abstraction in this region has resulted in problems during low flows and as a result releases from upstream dams are required to provide support to baseflows (Brunet *et al.,* 2003). Furthermore, on the River Torne, Yorkshire, the iWAIT project began in 2016 with the aim to deliver over 4000 cubic metres of additional storage in the catchment (Burgess-Gamble *et al.*, 2018).

Offline storage areas can divert flows from watercourses into channel-adjacent storage areas providing opportunities for enhanced recharge over permeable ground. When combined with gravity-fed drainage pipes, these storage areas can both rapidly fill (for flood storage and enhanced recharge) and drain (for future flood storage benefit) depending on operational requirements and inflow conditions (Nicholson *et al.,* 2019).

Infiltration trenches or swales have also been suggested to increase infiltration of overland flow. Infiltration trenches work through using porous media to filter stormwater to allow infiltration into the ground at a specific rate to increase groundwater recharge (Larson and Safferman, 2008). Whilst their application as SUDS is now relatively common, they also have potential within agriculture for capturing surface runoff and filtering sediments and pollutants such as phosphates (Zhao *et al*., 2016). However, in larger catchments clogging can occur due to sedimentation of the ground which can reduce infiltration rates, although control measures such as placing pea gravel over the porous media to trap sediment from entering the groundwater can reduce this.

The water supply mechanisms which support wetlands are diverse ranging from surface water dependent to groundwater dependent. Groundwater dependent wetlands are sensitive to periods of low groundwater levels, and this can be exacerbated by abstractions. Area of wetlands with high groundwater levels can in general maintain evapotranspiration rates at or close to potential evapotranspiration rates through drier periods until groundwater levels drop. However, this is a function of the aquifer in this area being full or close to fully saturated. Drainage/replacement of wetlands may reduce evapotranspiration losses but importantly at the expense of groundwater storage capacity and disruption to locally sensitive water regimes. Wetlands have specific and critical water regime requirements (Environment Agency, 2004; Whiteman *et al*., 2009; Wheeler *et al*., 2009) which are well documented through the series of ecohydrological guidelines developed by the Environment Agency, Natural England and leading academic partners.

Even in groundwater dominated catchments, flows may bypass wetlands. Therefore, in these situations, wetlands may play a greater role in the regulation of surface water quality (Prior and Johnes, 2002; European Union, 2015). Wetlands can achieve this by acting as a buffer for pollutants, trapping them and reducing pollutant loads in streams. Furthermore, in the Lambourn Catchment, Berkshire, UK, the exchange of flows between the gravel aquifer and the chalk river enables some attenuation of floodplain water-table variability and can provide a stable hydrological regime in the valley wetlands (Grapes *et al*., 2006). However, the flow in each individual catchment needs considering when managing wetlands in a permeable catchment.

2.6 Peatland Restoration

Restoration of damaged upland blanket bogs can slow runoff and increase and stabilise groundwater levels within in it. These systems can be damaged by a range of activities such as burning, grazing, atmospheric pollution, forestry and drainage. Restoration measures to restore the ecological and hydrological function of upland peat focuses on:

- blocking of drainage features,
- gully stabilisation and reprofiling,
- revegetation techniques,
- reducing intentional burning of moorland vegetation,
- reducing grazing pressures.

On the Kinder Plateau in Derbyshire, UK, revegetation and stabilisation of bare peat and implementation of gully blocking features were introduced, and after 3 years, the evidence demonstrated reductions in storm discharge by 375% and water tables raised by 35mm (Pilkington *et al*., 2015).

Shuttleworth *et al*. (2019) report on a before-after-control-intervention (BACI) study, from three experimental headwater micro-catchments in the South Pennines (UK), providing rigorous experimental assessment of the impact of blanket peat restoration on catchment runoff. The investigation shows the primary process controlling the observed changes in storm hydrograph behaviour was retardation of overland stormflow due to increased surface roughness with vegetation. Revegetation raised water tables by 35mm after 3 years and decreased peak storm discharge by 27%, it is expected that these benefits will be modified over time as vegetation matures, due to the increase in water tables being high it is likely that there are other factors within the catchment causing such a significant raise (Shuttleworth *et al.,* 2019).

Revegetation led to benefits to flood risk management, such as increased lag times and decreased peak flows. However, gully blocking was found to be almost twice as effective as vegetation in increasing lag times by lengthening time to peak by 94%. Increases in water storage after restoration of peat bogs produced greater water table stability and increases in water residency after rainfall (Wilson *et al.,* 2010). Restoration of peat bogs has been used in combination with gully blocking (that used wooden dams, peat dams or heather bales) to raise water tables. In the Lake Vyrnwy catchment in Wales, water tables were raised by 2cm when the two measures were combined (Wilson *et al.,* 2010).

Blanket bog drainage was discussed in Rogger *et al.* (2017) who stated that initial drainage of peatlands lowered the water table, increasing the near-surface water storage capacity. However, over time oxidation of peat caused by lowered water tables will result in a reduction in peat thickness and consequently reduce storage capacity.

2.7 River restoration, floodplain reconnection and wetlands

Promoting good connectivity between surface waters and groundwaters has been identified as a European Union-funded restoration initiative key requirement (European Union, 2015). This is particularly the case with the impact groundwater can have on low flows, water quality and ecology and this can influence the success of river restoration schemes.

River restoration through embankment removal in the River Glaven, which is underlain by a chalk aquifer, was found to reduce river capacity by 60% and facilitated overbank flow onto the floodplain (Cliverd *et al.,* 2013). This over-bank flow can enhance the intrusion of river water into floodplain sediments and underlying groundwater in permeable settings. This can be beneficial to groundwater resources, although consideration of the chemistry and potential impact on water quality should be carefully managed. The reduction in river capacity reduced the channel depth by 44% and the cross-sectional area of the channel by 51%. As a result, the water levels in groundwater wells closest to the river were elevated post-restoration potentially from enhanced river water intrusion.

Groundwater in upland floodplains can have an important function in regulating river flows and controlling the coupling of hillslope runoff with rivers, with complex interaction between surface waters and groundwaters throughout floodplain width and depth (O'Dochartaigh *et al.*, 2019b). In a study of Eddleston Water, Scotland, the investigation found a complex coupling between river flows and groundwater levels, with highly variable groundwater fluctuation across the floodplain. Whilst much of the aquifer in this catchment was hydraulically connected with the river, the groundwater levels near the floodplain edges were more dominated by sub-surface hillslope inflows. This has implications for seeking water resource benefits in zones of recharge and emergence at different lateral distances from watercourses.

Wetlands can enhance groundwater storage, although their response is often mixed and dependent on their location and hydrological conditions (Bullock and Acreman, 2003). However, their effect on the water budget can cause water shortages downstream due to increased evaporative losses and attenuation of flows. Wetland creation also provides wider benefits such as recreational amenity and habitat creation. In coastal regions, sand dunes can improve the rate of infiltration because of their low soil compaction and greater porosity and form a shallow aquifer for water storage under large dune systems to provide rapid groundwater recharge (Heslenfeld *et al.,* 2004).

Floodplain reconnection manages diffuse pollution by allowing accumulation of sediment loads. In the River Avon, Warwickshire, floodplain reconnection managed diffuse pollution because silt load was deposited on fields during a flood event, which reduced the silt load within the river (Burgess-Gamble *et al*., 2018).

2.8 Managed Aquifer Recharge

Managed Aquifer Recharge (MAR) technologies aim to increase groundwater resources by increasing infiltration into aquifers at times of water surplus and making available for abstraction at times of water demand. It can be implemented to secure water supply and compensate for the effects of climate change (Jakeman *et al*., 2016). Selection of the storage area for MAR is dependent on the availability of an aquifer, subsurface characteristics and the quantity and quality of surface water. When MAR is applied, it is important that these aquifers are confined otherwise the water stored in the aquifer will disperse and may not be available when it is later needed to be redrawn. It is important that any consideration of MAR takes into account existing Environment Agency (2017) position statements in relation to groundwater protection.

A less commonly practiced measure in the UK is Agricultural Managed Aquifer Recharge (Ag-MAR), this is used more widely in Australia and the U.S. A study using a Groundwater-Surface Water Simulation Model found Ag-MAR provides long-term benefits for water availability in groundwater (Kourakos *et al.,* 2019). Ag-MAR is a management practice that intentionally retains more water in groundwater aquifers than what would occur naturally. **Modelling between the period of 1990 to 2014 showed that recharge of excess surface water increased groundwater recharge by between 9 and 12% and raised groundwater levels up to 7-metres (Kourakos *et al*., 2019).** However, the issue of groundwater mounding associated with Ag-MAR was raised in the study, this is where Ag-MAR may cause waterlogging of crop roots or shallow soils and as a consequence could potentially damage crops and overlying land-uses. Therefore, the authors recommended that distributing a fixed recharge target volume over a season would eliminate the risk of groundwater mounding. Recharge amounts vary between months and years; thus, groundwater gains are dependent on seasonality. For certain measures such as Ag-MAR, their implementation needs to be ideally targeted during peak flow events.

MAR can also be used in urban areas to support urban water management to cope with variability in resources and runoff due to climate change. This is achieved by collecting surface waters in infiltration basins from stormwater runoff. However, storing water in urban areas is vulnerable to pollution from overlying land uses. Siting storage areas over confined aquifers minimises this vulnerability, but will limit infiltration (Page *et al*., 2018). In permeable areas MAR technologies are able to infiltrate polluted water. Some level of purification of the water may be provided by natural attenuation (physical filtering of actual particles, as well as dilution, dispersion and degradation) within the subsurface groundwater environment (Jakeman *et al*., 2016). However, the effectiveness of this depends upon the nature of the subsurface: the type and amount of porosity and permeability. Fractured aquifers, such as the chalk aquifer will allow very rapid infiltration, but minimal removal of contaminants. However, sands may provide a high level of pollution reduction. The groundwater vulnerability data set provides good general information about the sensitivity of the underlying groundwater to pollution risk. Specific sites proposed for infiltration should be assessed. Where water quality is an issue then treatment of the surface water prior to infiltration should always be considered. Wetlands and reedbeds could provide suitable treatment measures. Discharging contaminated water to ground in a manner which would derogate underlying groundwater quality is generally not permissible. The UK Government's Environmental Permitting Regulations (2016) and Environment Agency's (2017) approach to groundwater protection set out the legal requirements and position statements in relation to this. There is also a risk that if MAR is introduced in areas of unconfined aquifers and shallow water tables then localised groundwater flooding could be generated (Page *et al*., 2018).

An example MAR is the North London Artificial Recharge Scheme which was developed for drought management. The scheme used the confined Chalk and Basal Sands aquifers, it is reported to be the only large-scale operational recharge scheme in the UK (Harris *et al*., 2005).

Where it is not possible to increase storage of water in the ground, then storage of water above ground, such as in ponds, lakes, or reservoirs could also be considered.

2.9 Soil and Land Use management

It should be evident from the review so far that land use and land management can significantly impact the rate of recharge and the ways that soils are managed (or sometimes detrimentally compacted) and have the potential to affect terrestrial water cycles and pathways.

For example, in dryland cultivated upland sites, estimated recharge rates were 55-90mm/year (11-18% of mean rainfall) (Gates *et al.,* 2011). Whereas conversion of native vegetation to cropland in semi-arid regions increased recharge into underlying aquifers, resulting in water table rise. Gates *et al.* (2011) also demonstrated that larger rooted tree plantations reduce recharge into the soil and therefore shorter rooted vegetation should be used to benefit water resources: this has been a consistent finding throughout much of the literature. **Furthermore, under non-vegetated sites recharge estimates were 47-68mm/year compared to winter wheat cultivation as 33-55 mm/year and under apple orchards as only 9mm/year (Gates *et al.*, 2011).** Different soil management practices impact infiltration in different ways, for example soils receiving mustard green manures had infiltration rates 2 to 10 times greater than those not receiving manures (McGuire, 2003) due to increases in soil organic matter content. This is particularly important during dry summers to benefit water resources.

Practices that improve the soil structural conditions and soil stability are known to increase infiltration capacity, water storage capacity, and saturated hydraulic conductivity of soils and thus influence surface and sub-surface flows. Improved structural conditions of naturally-freely draining soils were found to maximise runoff reductions (Summers, 2015). Livestock removal and cover crops can be implemented to reduce runoff whilst providing wider benefits such as improved soil structure, diffuse pollution reduction and habitat creation (Wheater and Evans, 2009). Contour ploughing was found to reduce hydrological connectivity of flow paths and reduce field runoff, this would reduce diffuse pollution and allow water to be held back on the land and recharge through permeable ground (Harris *et al*., 2004). Cover crops can reduce surface runoff and erosion and increase the soil water storage capacity, this is because vegetation cover increases the surface roughness which reduces runoff, whilst vegetation additionally protects the soil and increases the soil's strength and load-bearing capacity (Patto *et al*., 1979). Cover crops reduce sediment production from cropland through intercepting runoff, and as a result, improve soil retention and quality. Changes to future climate could impact the effectiveness and ability to use cover crops. Cover crops are best adapted to warm areas with abundant precipitation to ensure that their water budget does not increase soil moisture deficits and reduce recharge. UKCP18 climate change projections suggest that precipitation is expected to increase by up to 33% in winter and temperatures are likely to increase by up to 4.2 degrees Celsius in winter MET Office (2018) which could be beneficial to the use of cover crops as a climate resilient WWNP measure. However, in summers less rainfall may subsequently adversely impact cover crop yields during periods of low rainfall (Dabney *et al*., 2007) and increase soil moisture deficits.

Sub-soiling is a common land management intervention that is used to improve aeration and enhance infiltration and recharge through pulling a sub-soiler device through arable or grass fields to break up compacted soils. Sub-soiling has the effect of increasing soil hydraulic conductivity, infiltration and water retention capacity (Burgess-Gamble *et al*., 2018). **A study found that following 2-years of sub-soiling on silt loam soil, infiltration rates increased by 10% across different types of tillage due to increased porosity, whilst erosion decreased by 278% with sub-soiling (Sojka *et al*., 1993).** Furthermore, in North Eastern Colorado, a 15cm deep slot mulch increased water infiltration which resulted in 41% more water being stored in the soil than in the untreated area (McConkey, ND). However, there are limited studies into sub-soiling in the UK and the benefits of soil aeration and enhanced infiltration depend on the soil type and the soil condition when the sub-soiling operation was undertaken and consequently the findings cannot be transposed as the impacts are likely to differ (Burgess-Gamble *et al*., 2018).

Repeating ploughing (as a form of tillage) is known to modify soil physical properties, through decreasing soil porosity, lowering the hydraulic conductivity and decreasing the bulk density of soils which can compact the soil beneath (Gomez *et al.*, 1999). Infiltration was greater under conventional tillage than areas of no tillage, however, in areas of no tillage, the soil had retained a moderate infiltration potential (Gomez *et al.*, 1999). Initial differences in the water content of the different treatments must be considered when looking into the results. Furthermore, **ploughing creates a layer that restricts water flow and root penetration, thus negatively impacting groundwater recharge and water resource availability (Carter and Colwick, 1971)**. A study undertaken in an olive orchard in Spain, found infiltration rates below olive trees in areas of no tillage were four times higher than in tilled rows between trees. This is thought to be caused by higher soil compaction in the rows between trees, which consequently reduces infiltration (Gomez *et al.,* 1999).

Groundwater recharge based on varying tillage practices on clay soils were found to be between 18.5-18.6mm/year (O'Leary, 1996). However, the study found certain soil management practices were more effective for recharge than others. For example: **stubble-retained subsurface tilled fallow (SRST), which disturbs soil below the surface, showed lower recharge of 2.2-3.8mm/year compared to conventional fallow**.

In comparison, **heavily grazed pasture was found to exhibit less than 50% of the infiltration rate of rotation pasture and overgrazing decreased infiltration due to decreased pore space in soils (McGinty *et al.*, 1978)**. Ilstedt *et al*. (2016) recommended that tree planting is not appropriate in areas of short rotation coppice or grazing because these activities prevent the input of organic material into soil and consequently reduce the ability for soil to infiltrate water.

The time of year in which crops are planted influences the runoff and infiltration balance. Maize is planted in wide rows running downslope. During autumn and winter when crops have been harvested (often by heavy machinery degrading already wet soils) and soils are bare, runoff increases and infiltration decreases because rainfall water cannot infiltrate through the compacted soils. During this period, increased runoff and eroded material concentrates in these downslope channels and may subsequently induce diffuse pollution (Palmer and Smith, 2013). On the Somerset Levels, farming of maize and potato crops in the surrounding catchments were found to increase the area of exposed bare soil in the winter months and thus reduce infiltration capacity. As a result, soil erosion and runoff increased and subsequently degraded water quality (Carver, 2016). Along with arable agriculture, livestock farming can cause soil structural degradation. In Pontbren, Wales, infiltration rates were significantly lower in grazed plots compared to ungrazed and afforested plots, this is because grazing (especially by large flocks of sheep) compacts the upper topsoil when the soil is wet (Marshall *et al.,* 2014).

The literature highlights that the relationship between soil and recharge are generally seasonally dependent. UKCP18 scenarios project that winters are likely to be stormier and wetter. Wind erosion and increased rainfall will result in greater soil exposure and subsequently, erosion and runoff will increase and pose a greater risk to flooding and diffuse pollution. As a result, it is important that soil structure and stability is improved to reduce these impacts which could potentially negatively impact water resources (Brazier *et al*., 2012).

Similar research undertaken in the Culm catchment, Somerset, found the water retention capacity of the Culm grassland (which has limited management) to be greater than nearby intensively managed grassland (Puttock and Brazier, 2014). The capacity in the Culm grassland was 241 litres per square-metre of surface area compared to 62 litres per square-metre of surface area in the managed grassland (Puttock and Brazier 2014). Therefore, the ability to store moisture decreases when grassland is more intensively managed.

Soils and geology are known to control the rates of infiltration and groundwater recharge and thus affect the storage capacity within soils and aquifers. Therefore, soils and geology determine the absence or presence of water in the subsurface, and control how flow contributes to flooding, baseflow and groundwater recharge. For example: annual average potential recharge in sandy soil was 38% higher than in loamy and clayey soil (Carbo *et al.*, ND). A study by Senerath and Rushton (1984) concluded that over lower permeability areas, a high proportion of effective rainfall was converted to surface runoff. Yet, over higher permeability strata within the same catchment, recharge to groundwater was almost double, highlighting the role that the permeability of soils and geology play in groundwater recharge.

The Chalk is the most significant aquifer in the UK, followed by the Permo-Triassic Sandstone. Chalk provides about 15% of the national water supply and 35% of the supply in southeast England. Its ability to supply large amounts of water are due to its fractured nature, and associated high transmissivity which allows rapid flow of groundwater. Groundwater discharges naturally from springs and as baseflow to chalk streams and is also pumped out of boreholes (Price *et al.,* 1987).

In contrast, less permeable deposits such as till (unsorted glacial sediment) can have a significant influence over recharge and soil moisture parameters (Fitzsimons and Misstear, 2005), with its **thickness significantly controlling the potential recharge coefficient. Recharge coefficients represent the proportion of effective precipitation that becomes actual recharge to the aquifer (Fitzsimons and Misstear, 2005). Recharge coefficients range from 4 to 30% in productive aquifers overlain by low permeability thick tills, whereas in areas characterised by thin, more permeable till, the recharge coefficients can range from 60 to 90% (Fitzsimons and Misstear, 2005).** Till was found to reduce potential recharge by 30%, whilst thick till deposits of North Yorkshire have been found to inhibit all recharge (Robins, 1998), opportunities to recharge via permeable till 'windows' such as identified in East Yorkshire (Burke *et al*., 2015) may still present some potential. Fitzsimons and Misstear, (2005) also suggested that through varying till thickness, recharge coefficients can vary between 2 to 80% due to vertical hydraulic gradients.

A study in the Eddleston catchment, Scotland, demonstrated that in low permeable areas of silt and/or peat, transmissivity can be as low as $50m^2$/ day. Whereas in coarse-grained floodplain alluvium, there can be higher transmissivities of $1{,}000m^2$/d (O'Dochartaigh *et al.,* 2019).

On fine-textured soils both sorptivity (ability for liquid to be absorbed by capillarity) and infiltration were significantly greater (up-to fivefold) under timbered land-use compared to on grassy or cultivated slopes (Eldridge and Freudenberger, 2005). Their research further concluded that increased infiltration under trees has benefits for soil nutrient concentrations which increase with proximity to tree trunks.

Lee *et al*. (2016) demonstrated that rapid responses in recharge rates are greater in winter because this is when the unsaturated (vadose) zone is the thinnest, the moisture zone is highest and there is significantly less evapotranspiration from plants or colder temperatures. The vadose zone extends from the ground surface to the water table. The unsaturated moisture zone is the depth of soil above the water table which roots, and plants extract water from. During higher rainfall intensities, recharge is likely to be enhanced due to the larger proportion of water that is available (Lee *et al.,* 2006). As the thickness of the unsaturated zone increases, so does the response time of the water table to rainfall events.

2.10 Literature Review Summary

For the purposes of improving water resource benefits, WWNP has been reviewed based on measures which are focused on improving water storage, reducing water losses or a combination of these.

Significant literature has been reviewed on the impact of varying land cover on water budgets. For example, shorter rooted and small-canopy vegetation is believed to increase recharge rates, whilst longer rooted and large-canopy vegetation such as trees is estimated to reduce average annual recharge rates particularly through reducing water budgets reaching the ground. However, where land cover influences recharge rates, the proportion of that land cover type is influential, for example recharge is optimal at a low to moderate planting density where woodland exists.

There is a wealth of literature on the impacts of tree planting across different geologies and using different species and densities across the UK. However, this is regionally biased and as a result, findings from one catchment cannot be necessarily transposed to other catchments that have different characteristics, thus highlighting a demand for more locally specific monitoring and research. Targeting of new woodland therefore needs to be more subtle in order to reduce potential dis-benefits where dense planting may reduce recharge. In addition to land cover, the underlying soils and geology are crucial in determining the absence or presence of groundwater storage and the recharge rates and pathways into these. Seasonality and climate were shown to be important for recharge rates, particularly where woodland exists.

It is therefore important that where tree planting is recommended for NFM amongst multiple other benefits, that this accounts for the potential detrimental impact on water resources if not properly managed.

A number of WWNP features (which is not exhaustive) which target improved water storage were reviewed and may provide positive benefits to water resources, flood risk management, water quality and biodiversity. These included runoff attenuation features, leaky barriers and large woody debris, peat bog restoration, river restoration, wetland restoration and offline storage. Storage features are typically most effective for groundwater resources if they overlie permeable geology and soils, although their potential to slow flows on less permeable geology may still have flood risk and recharge potential benefits further downstream.

The literature review also raised the important role that soils and their management can have on water resources, flood risk and water quality. There are a wide-range of practices which can be integrated as WWNP which may help reduce water losses (whether that be evaporative or as surface runoff), improve soil infiltration and increase the water available for recharging water resources.

To date, WWNP case studies in the UK have tended to focus on flood risk reduction, and surface water benefits in relation to water quality and ecology, research needs to incorporate how measures can be effective from a water resource perspective. Providing research through evidence on water resource benefits would help to strengthen and encourage WWNP uptake, evidence will additionally enable the scale of measures to be correlated with the scale of benefits to water resources that may be achieved. There is a need for on-going research into the benefits and impacts of combinations of WWNP measures on groundwater availability and quality, and a further need to quantify these. A research gap exists on identifying an integrated approach which combines the right kind of tree-planting in the right places, with appropriate land management practices depending on soils and geology, and with storage attenuation features and wetlands placed advantageously in order to enhance recharge rates and water resources, whilst seeking to maximise on multiple benefits.

2.11 WWNP Summary Matrix

In addition to the literature review, a WWNP summary matrix has been developed and is available in Appendix A. The matrix aims to consolidate the literature review so that relevant WWNP interventions are presented for their potential water resource benefits and dis-benefits, any wider multiple benefits and flagging areas to consider avoiding or carefully managing.

WWNP Measure Group	WWNP Measure Types	Project WWNP GIS Categories	WRB	Funding Scale	Potential Water Resource Benefits	Evidence	Potential Water Resource Dis-Benefits	Evidence	Multiple benefits	Areas to avoid
Upper Catchment Land and Runoff Management	Runoff attenuation storage features on hillslopes including ponds, bunds, infiltration trenches and swales	WWNP RAF WWNP CS		Small-scale capital construction	1. Improves water storage, promotes infiltration and groundwater recharge where sited over permeable geology	1. Larson and Safferman, 2008 1. Hankin et al., 2018 1. Zhao et al., 2016	1. Reservoir Act 1975 regulates areas of significant storage volume and this threshold may reduce in future 2. Sedimentation can develop over time and result in clogging reducing infiltration 3. Surface ponding can result in poor soil aeration and restrict infiltration	1. GOV.UK, 2010 2. Larson and Safferman, 2008 3. USDA & NRCS, ND	Slow and attenuate surface runoff for flood risk reduction and delayed recharge Capture and filter sediment loads Capture and filter diffuse pollutants Improved biodiversity and habitat creation	In close proximity to contaminated land which may mobilise pollutants In close proximity to abstractions sensitive to groundwater quality eg. SPZs Generating storage volume >10,000m3
	Peatbog restoration including grip blocking and vegetation restoration	WWNP RAF WWNP CS		Land management	1. Sustains groundwater level and raises water table 2. Kinder Plateau, Derbyshire- water tables increased by 35mm over a 3-year period 3. Water tables raised by 20mm in Lake Vrynwy catchment, Wales	1. Krause et al., 2007 2. Pilkington et al., 2015 3. Wilson et al., 2010			Slow and attenuate surface runoff for flood risk reduction and delayed recharge Capture and filter diffuse pollutants Improved biodiversity and habitat creation Carbon sequestration	Careful management around SSSIs
	Tillage/ploughing and sub-soiling management	WWNP SPS WWNP LCM		Farming Management	1. Conventional tillage can increase soil infiltration rates compared to no tillage 2. Sub-soiling can increase infiltration by 10% through enhanced porosity after 2-years 3. Slot mulch can increase infiltration and increase water storage by 41% 4. Contour ploughing can retain surface runoff for recharge	1. Lipiec et al., 2006 1. Gomez et al., 1999 2. Sojka et al., 1993 3. McConkey ND 4. Harris et al., 2004	1. Conventional tillage can reduce soil infiltration rates compared to no tillage 2. Modifies soil properties by decreasing porosity and lowering hydraulic conductivity.	1. Elliott & Efetha, 1999 2. Carter and Colwick 1971	Conservation tillage can reduce soil erosion and diffuse pollution rates	Avoid conventional tillage in areas of fragile and erodible soils, particularly on steep hillslope gradients
	Peatbog drainage			Land management	1. Short-term initial drainage increases near-surface water storage capacity	1. Rogger et al., 2017	1. Increased soil moisture deficit reducing groundwater recharge and oxidation of peat will lower water tables and reduce peat thickness and reduce water storage	1. Rogger et al., 2017		Careful management around SSSIs
	Land and in-field drainage features	WWNP SPS WWNP LCM		Farming Management	1. Reduces local water table improving soil storage capacity Can divert surface water to more permeable areas	1. Blanc et al., 2012	1. Can promote rapid surface runoff and exacerbate diffuse pollution	1. Blanc et al., 2012	Improved crop yield	Areas susceptible to surface water flood risk or flashy fluvial flooding

Figure 2-1: WWNP Summary Matrix Example

The following section provides further explanation to navigating through the WWNP matrix.

WWNP Measure Group

Grouping WWNP interventions on both their location within the catchment (upper/middle/lower/wider) and type (land/runoff/storage/planting management). Further explanation of the relevance of location within the catchment is provided within the generic conceptualisation in Section 4.

WWNP Measure Types

Individual WWNP interventions (or grouped where similar).

Project WWNP GIS Categories

Suggested GIS feature datasets provided as part of this project which may be relevant to delineating the areas of WWNP measure types.

Water Resource Benefit Indicator (WRB)

Provides a colour indicator of the overall evidence identified as to whether the WWNP interventions are likely to provide a water resource benefit with particular relevance to groundwater resources.

- WWNP features which typically provide a groundwater resource benefit based on the evidence, providing that relevant guidance and expertise are followed in their application to manage any associated risks and maximise their benefit.

- WWNP features which provide a mixed groundwater resource benefit based on the evidence. Water resource benefits are likely to be strongly dependent on location and have shown evidence both for, and against, improving groundwater resources. Further research and local investigations are recommended to better understand the application of this WWNP intervention. However, these interventions may will provide significant multiple benefits to balance with any groundwater resource impacts.

- WWNP features which typically provide a groundwater resource dis-benefit based on the evidence. WWNP interventions are likely to require expertise and careful management within the local environment to achieve a groundwater resource benefit. These features may still provide significant multiple benefits.

Funding Scale

Type of funding and implementation relevant to the WWNP measure types to improve targeting of funding (e.g. small-scale capital construction/major intervention/habitat creation – restoration/land management/farming management).

Potential Water Resource Benefits and Evidence

Listed benefits to water resources with particular relevance to groundwater resources and processes, supported by evidence (numbered).

Potential Water Resource Dis-Benefits and Evidence

Listed dis-benefits to water resources with particular relevance to groundwater resources and processes, supported by evidence (numbered).

Multiple benefits

Wider benefits that WWNP may provide in addition to potentially improving groundwater resources.

Areas to avoid

Key areas to consider more detailed investigation, management and potentially avoid prior to adopting and installing groundwater WWNP measures to minimise potential negative impacts to groundwater resources.

2.12 WWNP Examples

The following section provides illustrative examples of a number of WWNP discussed within this project. Further examples as well as case studies are available within the Environment Agency's Evidence Base[3].

3 https://www.gov.uk/government/publications/working-with-natural-processes-to-reduce-flood-risk

Eddleston Water – source: © Lydia Burgess-Gamble

Figure 2-2: Example Runoff Attenuation Feature Pond

Cranham, Gloucestershire - source: © Chris Uttley

Figure 2-3: Example Runoff Attenuation Feature Cascading Attenuation Ponds

Woodchester, Stroud - source: © Chris Uttley

Figure 2-4: Example Woody Debris Soil and Silt Traps

Peak District – source: © Lydia Burgess-Gamble

Figure 2-5: Example Peatland Restoration and Grip Blocking

Cumbria – source: © Lydia Burgess-Gamble

Figure 2-6: Example Gully Blocking with Woody Debris

Snows Farm, Slad Valley, Stroud – source: © Chris Uttley

Figure 2-7: Example Semi-Natural Large Woody Debris Structure

Belford Burn – source: © Nick Chappell

Figure 2-8: Example Leaky Timber Barrier

Swindale Beck – source: © Iain Craigen

Figure 2-9: Example River Restoration

Eddleston – source: © Lydia Burgess-Gamble

Figure 2-10: Example Wetland and Offline Storage

West Devon – source: © Lydia Burgess-Gamble

Figure 2-11: Example Beaver Enclosure

Swindale Beck – source: © Iain Craigen

Figure 2-12: Example Riparian Planting

Lorton, Cumbria – source: © Iain Craigen

Figure 2-13: Example Willow Floodplain Planting

Leen Farm, North Herefordshire – source: © Iain Craigen

Figure 2-14: Example Ryegrass Interseeding between Maize Crops

Leen Farm, North Herefordshire – source: © Iain Craigen

Figure 2-15: Example Hedgerow Planting

Soil aerator (near-surface equivalent to sub-soiling) – source: © Helen Keep, Yorkshire Dales National Park Authority

Figure 2-16: Example Soil Aeration

2.13 References

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3 Data Review

This section provides a summary of datasets that are relevant to this and future projects which are seeking to apply WWNP and/or interact with groundwater resources. Table 3-1 provides a list of relevant datasets and defines their potential application in relation to WWNP and groundwater resources and indicates if they are likely to offer WWNP or groundwater potential, constraints (areas to avoid), or contextual information. The existing WWNP potential features listed first have already filtered to remove areas within a 'national constraints' layer. This layer includes urban areas, roads, railways and existing significant woodland inventories.

The current licence level column provides details on whether the data is freely available (Open) or requires a conditional agreement which may have associated costs depending on intended application of the dataset. It is recognised that a number of BGS datasets are freely available for screening at an aggregated level (such as 1km hexagon grid), or available at a finer detail under a specific licence agreement.

The datasets defined in bold within Table 3-1 indicate those that have been taken forward as part of this project based on their level of detail applicable to the ten study areas and ability to be licenced. It is recommended that more detailed datasets are utilised, where available, and on-site ground investigation and local engagement are completed for any site-specific work, particularly where this may be close to an environmental or groundwater sensitive site.

It is important that any future projects seeking to utilise these datasets check for any recent updates. This is of particular importance for those which relate to potentially more frequent changes in operation, such as source protection zones and landfill sites.

Table 3-1: Data Review Summary

Dataset	Category	Potential Application	Licence
EA WWNP Runoff Attenuation Features Potential	WWNP Potential	Identify natural topographic depressions/surface water ponding to slow flows, enhance storage and increase potential recharge.	Open
EA WWNP Floodplain Woodland Potential	WWNP Potential	Identify areas within floodplain (Flood Zone 2 (FZ2)) outside of national constraints that may be areas to slow flows, reconnect with floodplains and increase potential recharge.	Open
EA WWNP Riparian Woodland Potential	WWNP Potential	Identify areas within 50m of watercourses outside of national constraints that may be areas to slow flows, reconnect with floodplains and increase potential recharge.	Open
EA WWNP Wider Catchment Woodland Potential	WWNP Potential	Identify areas for low-medium density planting on slowly permeable soils to improve soil structure, reduce surface runoff, slow flows and increase potential recharge.	Open
EA WWNP Floodplain Reconnection Potential	WWNP Potential	Identify areas of lower flood risk (where land is predicted to flood during extreme events with a 1% annual probability or rarer) inferred to be poorly connected to nearby watercourses to promote floodplain reconnection and river restoration to slow flows and increase potential recharge.	Open
EA 0.1% AEP Surface Water Flood Map	WWNP Potential	Identify wider natural topographic depressions/surface water ponding to enhance storage beyond runoff attenuation features and increase potential recharge. Identify surface water flow pathways for diverting flows into large managed aquifer recharge or smaller runoff attenuation feature areas/swales/bunds.	Open
EA Flood Zone 2 and Flood Zone 3	WWNP Potential/Constraint	Identify wider areas for potential floodplain reconnection that may be options for further river restoration, washlands and wetlands to slow flows, enhance storage and increase potential recharge. Identify areas downstream which may be susceptible to groundwater flooding or re-emergence or other sources of flood risk.	Open
CEH Land Cover Map 2015	WWNP Potential/Constraint	Classify land cover for identification of wider improved land cover management strategies eg. arable and grassland improvements or urban SUDS target areas. Constrain particular WWNP features that may not be practical in certain zones eg. within urban areas or existing woodland. Data is at land-parcel scale so greater precision than CORINE although of earlier publication.	Conditional (EA)
EEA CORINE Land Cover 2018	WWNP Potential/Constraint	Classify land cover for identification of wider improved land cover management strategies eg. arable and grassland improvements or urban SUDS target areas. Constrain particular WWNP features that may not be practical in certain zones eg. within urban areas or existing woodland (less precision than Land Cover Map).	Open
NE Agricultural Land Classification Provision	WWNP Potential/Constraint	Identify areas of classified highest/lowest agricultural land quality that may encourage/constrain allocation of land to WWNP measures. Grades already account for flooding frequency, although may be subjective.	Open

Dataset	Category	Potential Application	Licence
EA Historic Flood Map	WWNP Potential/Constraint	Identify areas downstream which may be susceptible to flooding (source of flooding may not be well documented), may provide an indicator of areas susceptible to groundwater flooding or re-emergence.	Open
EA Flood Storage Areas	WWNP Potential	Understand catchment hydraulics and existing regulated storage (only covered in Brue AoI for areas covered in this project).	Open
EA Groundwater Vulnerability	WWNP Potential/Groundwater Context	Identify (at national-scale) risk of surface pollutants infiltrating into groundwater resources. Generally this data set can be used as a proxy for opportunities for increasing recharge. High vulnerability = high potential for changing recharge. However, risk assessment should be undertaken close to groundwater supplies. Comprises information on drift cover, thickness and permeability which can be used to inform potential recharge.	Conditional (BGS/EA)
NE Sites of Special Scientific Interest	WWNP Context/Groundwater Constraint	Review sensitivity of SSSI as a potential constraint to interventions or a potential for ecological WWNP multiple benefit, some will also be SACs.	Open
EA Groundwater Dependent Terrestrial Ecosystems	WWNP Context/Groundwater Constraint	Review sensitivity of SSSI (specifically those with wetland vegetation communities) as a potential constraint or ecological benefit to WWNP interventions. Groundwater levels are likely to be close to the surface at GWDTEs, they may also be a natural groundwater discharge area and so not suitable for trying to increase recharge.	Open
NE Special Areas of Conservation	WWNP Context/Groundwater Constraint	Review sensitivity of SAC as a potential constraint to interventions.	Open
EA 2m LiDAR Digital Terrain Model	WWNP Context	Provide precise topographic data for understanding potential surface and groundwater flow paths, and for developing cross-sections for groundwater conceptual model schematics.	Open
EA National Receptor Dataset 2014	WWNP Context/Constraint	Assess number and type of properties downstream from interventions which may benefit from flood risk reductions (primarily focused on surface water and fluvial sources). Best applied directly to model outputs as part of a detailed impact assessment.	Conditional (EA)
EA WFD Groundwater Status	WWNP Context	Understand most sensitive groundwater areas for potential opportunities to improve water quality and water resources.	Open
EA WFD Surface Water Status	WWNP Context	Understand most sensitive surface water areas for potential opportunities to improve habitats and water flow and quality. For example, improving recharge may provide a baseflow benefit to improve surface water low flows.	Open
EA Nitrate Vulnerable Zones	WWNP Context	Understand most sensitive groundwater and surface water areas for potential opportunities to reduce nitrates.	Open
JBA Groundwater Flood Risk Map (5m resolution) **See Appendix B for outline**	WWNP/Groundwater Potential/Constraint	Predicted groundwater flood levels in relation to ground surface to identify: areas where recharge is always possible (if geology is suitably permeable); where elevated levels may reduce recharge potential (potentially seasonally); and areas possibly susceptible to increased groundwater flood risk under increased recharge or reduced abstraction operations. These areas should seek more detailed groundwater flood risk assessment.	Conditional (JBA)

Dataset	Category	Potential Application	Licence
BGS Groundwater Flood Risk Map (50m resolution)	WWNP/Groundwater Potential/Constraint	Identify groundwater flood risk categories where groundwater may be close to the surface which may reduce recharge potential (potentially seasonally) and indicate areas which may be susceptible to increased groundwater flood risk under increased recharge or reduced abstraction operations. These areas should seek more detailed groundwater flood risk assessment. Areas with no groundwater flood risk may always allow recharge, if the geology is suitably permeable.	Conditional (BGS)
CEH BFIHOST 1km^2 Grid	Groundwater Context	Understanding contribution that groundwater/baseflows have on the hydrology within 1km2 grid squares. Areas of higher BFI have greater connection to groundwater and more potential for changes to recharge. However, areas with extremely high BFI may have less scope for increasing recharge, as it is already occurring.	Conditional (EA)
BGS 50k Geology	Groundwater Context	Understanding the superficial, bedrock and fault geology to identify permeable and impermeable areas and aquifers.	Conditional (BGS/EA)
BGS 625k Geology	Groundwater Context	Understanding the superficial, bedrock and fault geology (reduced accuracy and detail compared with 50k dataset, therefore most suited to screening rather than detailed assessment) to identify permeable and impermeable areas and aquifers.	Open
BGS Superficial Deposit Thickness	Groundwater Context	Understanding the potential for superficial deposits to restrict or benefit recharge into both superficial and bedrock aquifers. Note: the advanced superficial thickness model information is also included within the EA groundwater vulnerability dataset.	Conditional (BGS) for Detailed or Open for 1km Hexagons
BGS Infiltration SUDS Map	Groundwater Context	Understand ground suitability for infiltration including constraints, drainage (including permeability), ground stability and groundwater protection. Whilst targeted to infiltration SUDS, this could also be applicable to WWNP promoting enhanced infiltration. Note: the groundwater protection datasets may not reflect the latest EA data.	Conditional (BGS)
BGS Hydrogeology 625k	Groundwater Context	Identify aquifers and their productivity (at a national scale) reduced accuracy and detail compared with EA aquifer designation datasets or ModelMaps where these exist.	Open
EA Aquifer Designation Superficial	Groundwater Context	Identify superficial aquifer type and relative groundwater storage (at a national scale) for identifying areas to recharge superficial deposits.	Conditional (EA)
EA Aquifer Designation Bedrock	Groundwater Context	Identify bedrock aquifer type and relative storage (at a national scale) for identifying areas to recharge bedrock aquifers.	Conditional (EA)
EA ModelMap	Groundwater Context	Provide contextual understanding of local groundwater processes and review of groundwater model outputs (where groundwater models and ModelMaps are available).	Conditional (EA)
LandIS NATMAP Soils (NATMAPvector)	Groundwater Context	Identify soil types and understand permeability and soil drainage capability for understanding potential limitations to recharge.	Conditional (EA)
EA Resource Availability at Q95	Groundwater Context	Identify (at a national scale) areas of greatest water resource pressures, which may be at a priority to improve water resources (note: several areas are due update with local expertise since last published).	Open

Dataset	Category	Potential Application	Licence
MET Office MORECS/EA MOSES Potential Evapotranspiration	Groundwater Context	Identify/estimate the total amount of effective rainfall available for recharge infiltration or runoff which may prioritise areas for water resource improvement in more detailed assessments.	Conditional (MET Office/EA)
EA/SMHI CSF (Catchment Sensitive Farming)-HYPE Derived Datasets	Groundwater Context	Inform local hillslope hydrological connectivity processes at the WFD waterbody catchment-scale including rainfall-runoff and water quality responses to inform more detailed assessments. Note: areas of chalk require incorporation of groundwater modelling to constrain uncertainties.	Conditional (EA)
Durham University/EA SCIMAP	Groundwater Context	Inform more detailed assessment local hillslope hydrological connectivity processes and identification of potential diffuse pollution sources which may provide WWNP multiple benefits.	Open
EA Groundwater Vulnerability Soluble Rock Risk	Groundwater Constraint	Identify (at national-scale) risk of solution of the ground and potential subsidence due to additional infiltration of recharge, 1km^2 grid squares. Seek expert hydrogeologist advice to understand potential risks of increasing recharge in areas at risk of solution.	Conditional (BGS/EA)
EA Groundwater Vulnerability Local Info	Groundwater Constraint	Further refine groundwater vulnerability, constraining interventions where increased risk to groundwater supplies.	Conditional (BGS/EA)
EA Historic Landfill Sites	Groundwater Constraint	Any WWNP which might impact on historic landfills or contaminated ground should have a specific risk assessment. Raising groundwater levels or recharge within waste could result in more leachate generation, increased recharge up-gradient could result in higher groundwater flow rates and faster contaminant migration. Down gradient measures could include wetland which might (depending upon contaminants and flow paths) have the potential to improve (ground)water quality.	Open
EA Authorised Waste Sites	Groundwater Constraint	Constrain interventions upstream/downstream from contaminated land which may pollute groundwater supplies. Consider impact of activities up-gradient on the landfill and any leachate generation (eg. is the landfill fully lined?) and promote site investigation.	Open
BGS Mining Hazard 1km Hexagons	Groundwater Constraint	Identify regions of historic mining activity that may be a proxy for contaminated land and/or subsidence. Increasing recharge in these areas may result in generation of acid mine drainage. A site-specific risk assessment should be undertaken. In some areas mining at depth will not impact upon near-surface groundwater flow paths.	Open
EA Closed Mining Waste Facilities	Groundwater Constraint	Constrain interventions upstream/downstream from contaminated land which may pollute groundwater supplies. None specified within this project's areas.	Open
EA Source Protection Zones	Groundwater Constraint	Where water resources are limited, additional recharge in these areas could be very beneficial for water resource status. However, care should be taken not to reduce water quality and the Environment Agency's Approach to Groundwater Protection (2017) should be consulted. For any interventions that may disturb groundwater within SPZ1 a full risk assessment should be undertaken in conjunction with liaison with the EA, many measures may not be suitable. Review interventions that may disturb groundwater within SPZ2 and SPZ3 with expert hydrogeologist advice and following EA SPZ guidance. Some overlap but identical with DWSZs.	Open

Dataset	Category	Potential Application	Licence
EA Drinking Water Safeguard Zones (Groundwater)	Groundwater Constraint	Review interventions that may disturb groundwater within DWSZs with expert hydrogeologist advice and following EA guidance. Some overlap but not identical with SPZs - based initially on SPZ2 with additional updates.	Open
Notes: **Bold text** denotes application within this project BGS – British Geological Survey; CEH – Centre for Ecology and Hydrology; EA – Environment Agency; EEA – European Environment Agency; JBA – JBA Consulting; LandIS – Land Information System; NE – Natural England; SMHI - Swedish Meteorological and Hydrological Institute			

4 Generic Conceptual Models

4.1 Introduction

As highlighted within the literature review, WWNP covers a broad range of potential measures that can be applied across different parts of a catchment. The Evidence Base (Burgess-Gamble et al., 2018) clearly lists out and groups potential measures throughout the catchment and outlines their potential multiple wide-ranging benefits. Further hydrogeological and geological guidance in applying NFM is specified within the Working with WWNP Evidence Base SC150005 (Environment Agency, 2017) and should be considered alongside this report when implementing WWNP in groundwater sensitive sites. This includes outlining the importance of permeability, groundwater flooding mechanisms, multiple benefits, geohazards and statutory obligations.

The following section aims to specifically discuss how WWNP measures can potentially improve groundwater resources which forms the primary aim of this project.

4.2 Generic conceptualisation of WWNP and groundwater

Overall, for groundwater resources enhancement the interest is in getting more recharge into the ground to provide a greater volume of groundwater resource and enhanced baseflow during dry periods. This may additionally result in less flooding as another benefit as peak runoff values may be reduced, although any potential to increase groundwater flooding should be considered and managed. There is also interest in measures which may improve water quality, of both surface and groundwater.

It is possible that measures which may have benefits for natural flood management (NFM) may have disbenefits for water resources, e.g. measures which increase evapotranspiration and interception of rainfall (dense woodland), may reduce flooding but also reduce recharge to groundwater.

The following paragraphs highlight measures with regard to groundwater which are applicable in different zones of a surface water catchment. In many areas groundwater flow follows topography in a general manner; although, depending upon geology, groundwater catchments may be different from surface water catchments. These are generalisations and applicable to sub-catchments at a wide variety of scales.

To accompany this discussion are two figures.

Figure 4-1 which indicates the key processes that can be affected by WWNP interventions and their location in the catchment. Accompanying the diagram is a box outlining land use and management areas which might be achieved across the catchment zones. Figure 4-2 provides a version of the same diagram including generic intervention types.

The division of the catchment in the discussion is also reflective of the length of the flow path: from the initial run-off generation/infiltration split, to losing water to ground along run-off flow paths, to increasing the storage of aquifers. This means that run-off/infiltration splits, for example, are discussed in the Upper Catchment section, but the principles hold true throughout the catchment. There is no set scale for these elements and it is quite possible under this broad classification for a single field to have an upper, middle and lower catchment. It is also recognised that measures regarding land use and land management practices are applicable in all areas.

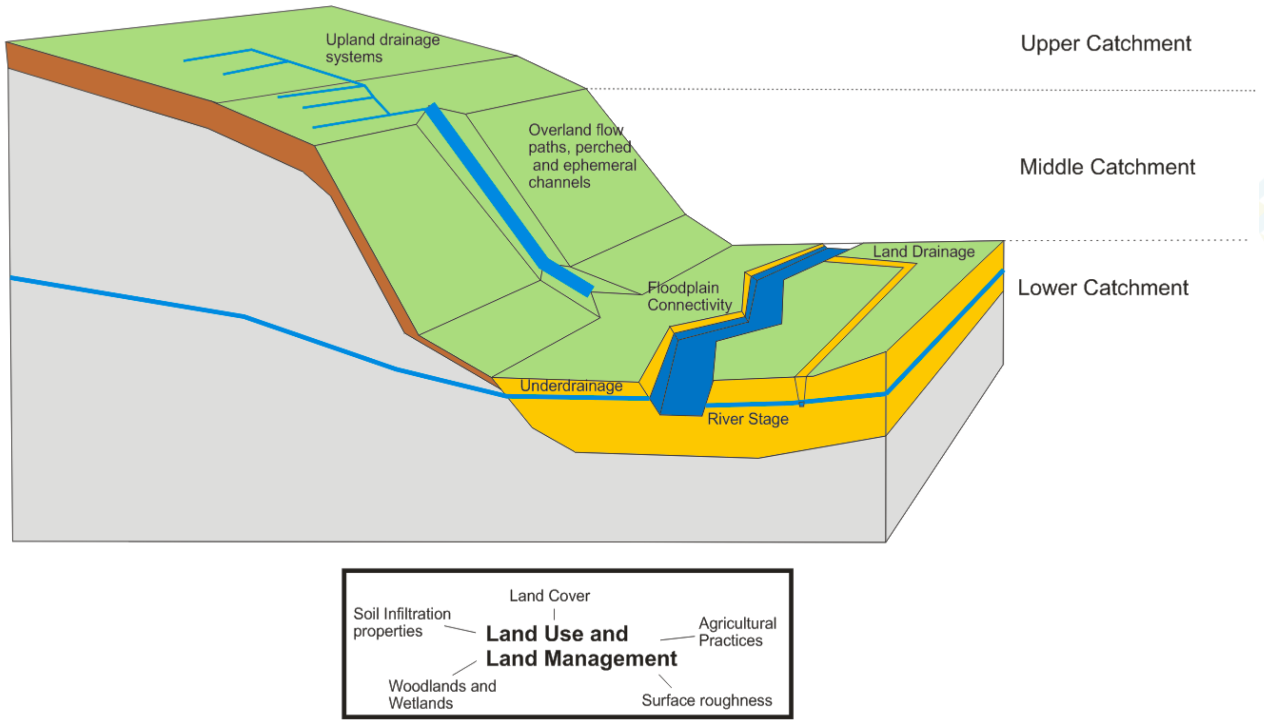

Figure 4-1: Generic Catchment Sub-division and Locations of Key Processes

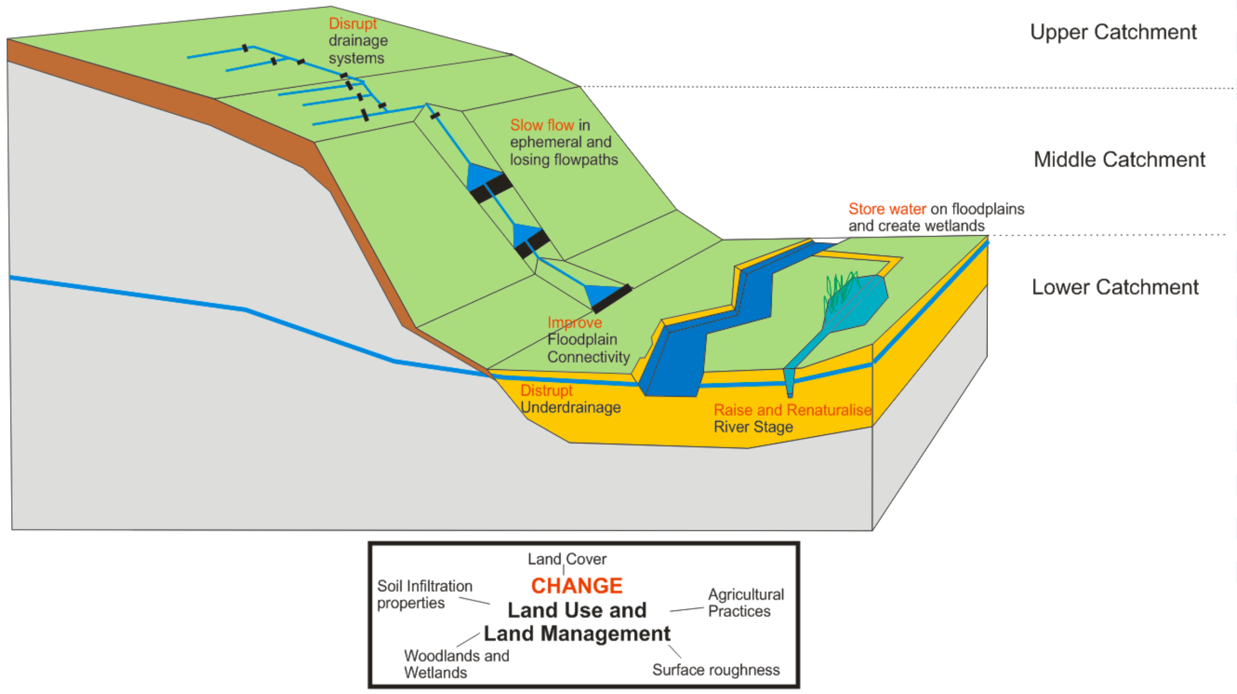

Figure 4-2: Catchment Sub-Divisions and Generic Intervention Types

Upper catchment and upland areas

In upland areas, distant from main rivers, the variables available to influence recharge include land cover changes and land management techniques. In particular, soil management and the vegetation presence (or absence) are key to infiltration, runoff and evapotranspiration. These have the ability to change the Hydrologically Effective Rainfall (HER) – by changes to evapotranspiration (HER is defined as rainfall minus evapotranspiration). Additionally, in these areas the regional groundwater level in aquifers may be at depth with a reasonable thickness of unsaturated zone. This provides significant scope for raising groundwater levels.

The destination of HER can be altered by land management techniques regarding changing the amount of recharge entering the ground compared to runoff into watercourses. The balance of recharge to the ground compared to runoff to the drainage network is influenced by:

- **Infiltration capacity of the ground** – how fast recharge can enter the ground before it is waterlogged. Once the ground surface/soil is saturated then runoff will be initiated. Soil management is critical for determining soil infiltration capacity.
- **Proportion of time there is Soil Moisture Deficit (SMD)**: when there is a SMD this has to be overcome before infiltration to the ground can occur. However, soils and sub-surface geology which are prone to cracking (eg. naturally fissured or cracking in dry weather) may permit bypass recharge.
- **Structure of the soil** including:
  - Macro pores/fissures which allow bypass recharge which can enable recharge to the ground even when a SMD is present. Bypass flow is often responsible for summer recharge to aquifers. Soil management and vegetation which increases bypass flow will have benefits for recharge. Compacted soil has more limited ability to allow infiltration of water. Soil management measures are critical in determining soils structure.
  - Surface roughness (discussed below).
- **Drainage measures** are key to how water moves through a catchment. At a field level, field drainage systems (including tile drains, perforated plastic pipes, mole drains, foot drains, etc.) and drainage ditches can intercept potential recharge to the ground and divert it to the surface water drainage network. This is discussed further in the next section.

The interaction of measures is important for the overall response of an upper catchment area and the net recharge and water quality achieved. For instance, while bare earth may have a lower evapotranspiration rate, it may be associated with higher rates of runoff as there is no vegetation to slow down runoff or the soil surface becomes capped. The runoff from bare soil may also contain higher levels of sediment which may both result in degrading of the soils resource and sediment problems downstream within watercourses. There is scope for further research into the combined impact of a number of WWNP land use and land management measures, rather than their use in isolation.

Measures which alter HER also include change to land uses with lower evapotranspiration. Different land uses, such as different crops, have different water uptake requirements. They also have variable albedo and differing typical patterns of Soil Moisture Deficit (SMD) and different rooting depths. Some crops also require artificial inputs of water from irrigation systems to allow them to reach their yield potential (when rainfall amounts are insufficient) which complicates the situation further as the irrigation water is obtained from surface water sources and groundwater sources.

Middle catchment and valley sides

In the middle of catchments there is still potential for enhancing recharge by land cover and land management techniques but additionally drainage management is also important.

Drainage paths are key**:** where drainage paths are quick and short then runoff is removed from the upper area without allowing much time for any effective infiltration to the ground. Where drainage paths are slower, longer or include ponding in the landscape then there is more opportunity for leakage of water from losing watercourses into the ground. The opportunity for water to leak into the ground requires the local groundwater level to be below the base of the drainage channel. That is**:** leakage from a losing watercourse can be increased, but if the watercourse is naturally gaining this isn't easily changed. However, it is noted that some mid-catchment watercourses are likely to be predominately losing, but some will have gaining periods depending upon the time of year and the elevation of groundwater levels relative to surface water levels.

Measures by which drainage can be modified to increase recharge to the ground include increased roughness of the runoff pathways resulting in slower runoff or diversion and storage of runoff from key drainage paths:

- At a field level this can include:
    - Changing the surface roughness through the presence of vegetation, rather than bare soil, eg. through cover crops in winter when arable soils may otherwise be bare or just covered by the stubble from the previous crop.
    - Contour cultivation and ploughing so that furrows and vehicle tramlines are perpendicular to drainage paths.
    - Thicker vegetation rather than over grazing and soil erosion or compaction, relevant especially for peat uplands.
    - Smaller fields with hedges, buffer strips and agroforestry (strips of woodland within fields), where these are orientated along contours in the landscape they will intercept drainage paths.
- Within drainage pathways this can include:
    - Increasing path length through fewer drainage ditches, or other drainage features. In peatlands this could the blocking of grips (regular drainage ditches) so that overland drainage path lengths to larger streams are longer.
    - A variety of different types of Runoff Attenuation Features (RAF) including swales, ponds, sediment traps, ditch roughening and widening and leaky dams. Providing these are situated on permeable geology, these features can not only improve groundwater resources but also critically drain down between storm events to increase the available storage for subsequent storm events and resilience (Figure 4-3). It is worth noting that a designed storage feature should aim to fully drain down between events (within 1-2 days depending on volume) by either including a pipe through the base of the bund or making the bund 'leaky'.

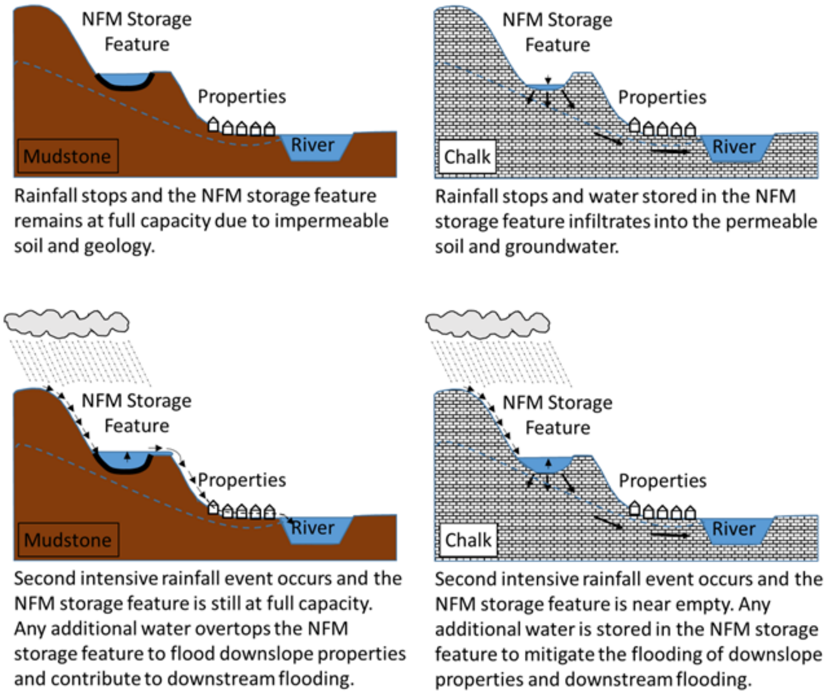

Figure 4-3: Runoff Attenuation Feature processes over varying geology (source: Environment Agency, 2017)

There is also the potential in upper and mid catchment areas for more formal reservoir storage of water. Depending upon how this is designed and/or operated this can provide summer water, e.g. irrigation for farmers, storage of flood waters and reduction in peak flows and wildlife benefits[4].

WWNP measures may be combined, for instance RAFs may be directed to woodland areas where they may infiltrate (tree roots may allow enhanced infiltration) and dissipate. Woodland can also provide considerable water quality benefits, e.g. sediment removal and also provide shelter over soils to reduce their evaporative losses.

Lowland catchment areas

Whereas the upper catchment and middle catchment are likely to be areas dominated by groundwater recharge, the lower areas are likely to have the groundwater-table close, or at the surface, and be predominantly groundwater discharge areas. There are often springs (discharge of groundwater) located at the change of slope between the valley sides and valley floor. There is generally likely to be baseflow to lowland rivers, which will in turn be mostly gaining rather than losing. One exception is rivers which provide navigation or high-level water carriers which may be perched above the wider water table. However, there are still measures which can be implemented to improve water resources, this is especially the case in areas of locally important alluvial aquifers. There are significant opportunities regarding river morphology, water quality and floodplain management. The following measures are particularly relevant in lowland areas:

- Connectivity between the river and its floodplain. Where rivers can flood over their floodplains there is the opportunity for infiltration into superficial sediments

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4 https://www.rspb.org.uk/globalassets/downloads/documents/futurescapes/water-for-farmers-and-wildlife.pdf

within the wider river valley. During a flood event or high level in the river then temporarily river levels will be above nearby groundwater levels and so there is the potential for some additional floodplain recharge. This may be significant in small alluvial aquifers. The proximity of the river to these alluvial aquifers means that this additional recharge may return fairly rapidly to the river as baseflow. However, care should be taken when attempting to increase recharge in areas of river valleys as raising groundwater levels in these areas may result in water logging or groundwater flooding, as groundwater levels are typically naturally close to ground surface. However, this can be successfully managed in some cases by a water meadow approach to managing fields. The JBA groundwater flood map (outlined in Appendix B and illustrated within each priority catchment's Area of Interest (AoI)), shows areas predicted at risk of near surface groundwater or groundwater flooding and these areas should only be targeted for increased infiltration if the land use is compatible with high groundwater levels.

- Use of water meadows, rotational flooding of agricultural fields, or paludiculture (wet agriculture) in lowland areas has a number of potentially positive effects including:
    - Reduction in farming pests and pathogens (including potato cyst nematodes);
    - Enhanced soil fertility and tilth;
    - Reduced farming inputs and higher quantity and quality of yields;
    - Schemes include wetland cycles on a 1-4 year rotation 'Walking wetlands' or continual management as water meadows;
    - Support for water bird species;
    - Schemes may have significant costs and clay fields may compact and take time to return to agricultural production.
    - Reduced loss of carbon from vulnerable peat based soils.
- Restoration of geomorphology of the river and its floodplain can provide water quality benefits including reduction of sediment and improved water storage. Measures which may be applicable are:
    - Restoration of natural bed profiles may raise the stage of rivers, and so increase the height of the adjacent groundwater discharge boundary. This may significantly increase the volume of groundwater stored within alluvial aquifers, especially where there has been historic incision of channels.
    - Riparian planting may help to slow the flow and promote overbank spill areas which may be beneficial for increasing recharge to floodplains.
    - Wetlands are beneficial for storing water and allowing slow release of water following a flood event.

4.3 Geology and Hydrogeology

In order to conceptualise the WWNP measures relevant in a particular area the generic measures indicated above need to be combined with the actual geology and hydrogeology within the specific catchment of interest. The following features are key:

- **Permeability of the soil** – soils are frequently permeable if the underlying sediments are also permeable. Soil type is very important where flooding of soils is considered, e.g. in river valleys and flood plains, clay soils will hold water well but take longer to dry out and return to production following flooding. Lighter more permeable soils will allow much more infiltration and through flow of water and dry out quicker.

Permeability of the geology – the sub-surface geology needs to have a permeability which allows recharge at significant levels. Very low permeability sediments, such as clay and mudstone are generally saturated as any recharge on them takes a long time to flow away. Additionally, they do not have significant available storage for recharge. The Environment Agency aquifer data (see Table 3-1) set can be used as a screening tool to assess if permeable geology is present. Furthermore, the national groundwater vulnerability dataset can be used as an approximate proxy for the potential for infiltration through the soil to reach groundwater. This is because it takes into account the potential protective layers above the water table including soils, superficial deposits and unsaturated zone that control the ability for surface water to reach the groundwater. In areas of high groundwater vulnerability there is a high potential for infiltration to groundwater[5]. Similarly, the BGS SuDS and permeability (1:50,000) datasets can used in more detailed assessments to estimate the potential for infiltration into the ground and also locations with sensitivities limiting the applicability of infiltration[6]. The constraints applicable to SuDS will also potentially be relevant for WWNP measures and should be considered as part of any detailed assessment of WWNP within a catchment, as follows.

- **Groundwater levels relative to the surface and surface waters:**
    - **Groundwater levels below ground surface and below surface water levels:**
        - Where groundwater levels are below the ground surface there is potential for recharge to the ground; and
        - Where groundwater levels are typically below the surface water levels i.e. rivers/streams/drains are perched, there is potential for leakage from surface waters to recharge the ground. These conditions are more typical of upper and mid catchment areas.
    - **Groundwater levels above surface water levels or very close to the surface**: these areas will be predominantly groundwater discharge areas with baseflow to rivers and potentially waterlogging of the ground with a risk of groundwater flooding**.** These conditions are more typical of lower catchment areas.
    - **Groundwater heads or piezometric levels may vary with depth beneath the ground**.

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5 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/660616/Groundwater_vulnerability_report_2017.pdf

6 https://www.bgs.ac.uk/products/hydrogeology/infiltrationSuds.html

        - Generally, in recharge areas there is a downward hydraulic gradient (i.e. the groundwater piezometric head is higher near the surface than at depth and this drives downward recharge). Conversely in areas of groundwater discharge there may be an upward hydraulic gradient where groundwater head increases with depth.
        - There may be different heads in superficial and bedrock aquifers which again will drive flow between the aquifers. Within a predominantly recharge areas, where there is recharge to a superficial aquifer then this may subsequently recharge a deeper aquifer.
    - **Areas of pumped drainage**
        - Lowland areas where water management is predominantly via pumped drainage have to some extent been avoided in the areas of interest in this project as the dominance of drainage means that measures to raise groundwater levels/recharge are not likely to be effective. The effect of a high-density drainage network discharging into larger drains which are then pumped is to limit maximum groundwater levels and lower average groundwater levels. Typically, these areas were naturally water-logged and may have been 'reclaimed' by drainage for agriculture. Decreasing drainage and raising water levels in these areas may not be compatible with current land uses.

4.4 Generic to Site Specific Conceptualisation

The following sections and standalone reports combine the generic WWNP and groundwater conceptualisation with the specific geology and hydrogeology characterisation of the AoI identified within Priority Catchments. The Priority Catchments each have significant water resources concerns. The AoI were identified by the Environment Agency and refined in discussion with the JBA project team. The AoI were selected to include principal bedrock aquifers where present in the priority catchment, these are likely to be significantly permeable, and a range of superficial sediments including secondary aquifers.

5 Conceptual Model and WWNP Potential Key Summary: Idle and Torne

The following section summarises the key findings from the Idle and Torne AoI. Further information on this catchment including details from the site visit, local stakeholder engagement and potential WWNP measures can be found within its catchment-specific report.

The conceptual model of the area is shown in Figure 5-1 and a version incorporating how WWNP interventions could be incorporated into the landscape is shown in Figure 5-2.

The AoI lies in the mid catchment of the Idle and Torne and is characterised by small valleys in sandstone bedrock with permeable soils and limited permeable superficial deposits. There is a very strong baseflow signature in the surface waters indicative of: the high rainfall infiltration rates to the Sherwood Sandstone; the contribution of baseflow from the upstream Magnesian Limestone Cadeby Formation; and potentially the upward vertical leakage from the confined Cadeby Formation. Much of the area has been undermined and has subsided. This has resulted in lowering of the land surface relative to groundwater levels (which have risen relative to the ground) with some subsidence flashes (new lakes) appearing and cracking of the bedrock.

Much of the interfluve areas are wooded, with arable land concentrated on the valley sides. Valley bottoms are typically narrow. There is already likely to be considerable recharge from rainfall: as indicated by the high BFI HOST values present. Most significant opportunities for increasing recharge in this mid catchment area are likely to be drainage interventions to increase infiltration from surface water runoff. This would have the effect of decreasing the effective standard percentage runoff (SPR) from significant rainfall events.

There are numerous ‘dry’ valleys which could be blocked or partially blocked to enhance infiltration recharge during extreme or significant rainfall events.

There is also some scope for increasing rainfall recharge through land management. The wooded areas could potentially be managed to allow less continuous woodland, less coniferous wood compared to deciduous woodland and drainage which prioritises infiltration. The arable land could be manged for soil conservation and infiltration with measures to increase drainage pathways. Currently intensive agriculture is highly demanding of water at key stages to grow produce of the required quality. However, less intensive agriculture could have a lower water demand and less irrigation requirements.

The valley bottoms are fairly limited in extent. However, depending upon the interaction of local topography with the more regional Sherwood Sandstone groundwater table there may be potential for leakage to the sandstone from valley bottom reservoirs/lakes/ponds.

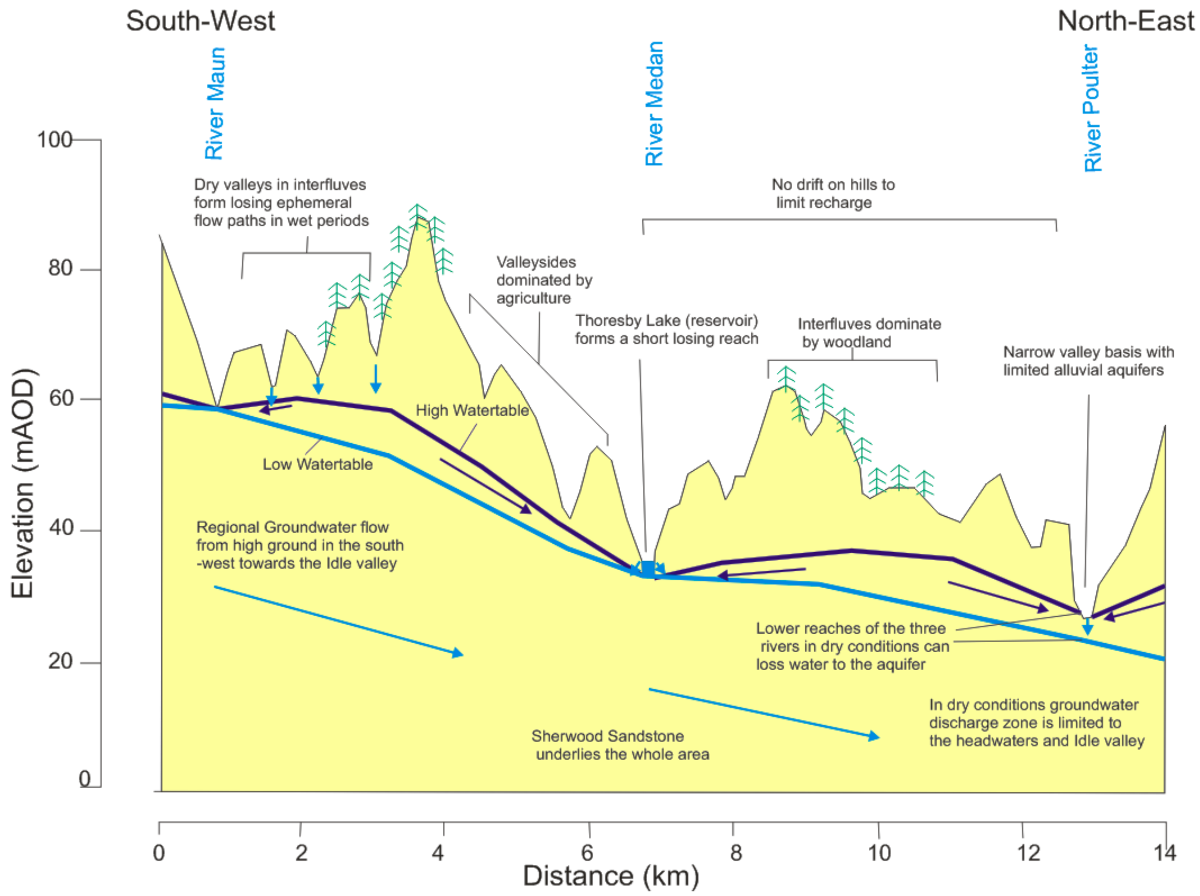


Figure 5-1: Idle and Torne AoI Conceptual Model

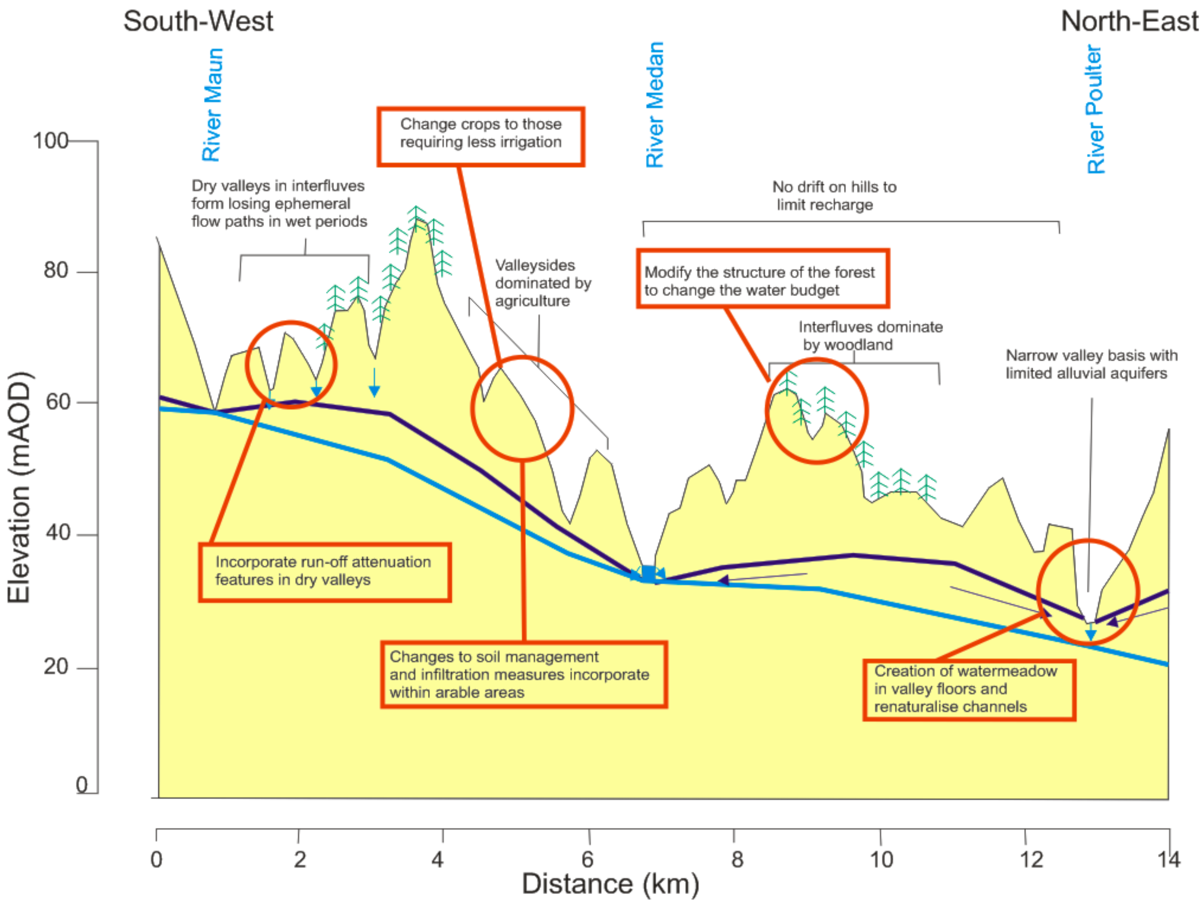


Figure 5-2: Idle and Torne AoI Conceptual Model with WWNP Measures

6 Conceptual Model and WWNP Potential Key Summary: South Forty-Foot

The following section summarises the key findings from the South Forty-Foot AoI. Further information on this catchment including details from the site visit, local stakeholder engagement and potential WWNP measures can be found within its catchment-specific report.

The hydrogeological conceptual model is shown in Figure 6-1. It has the following features:

- Topography:
  - The area slopes eastwards over 12km and ground elevations fall by 50m in that distance.
  - The eastern part of the area lies in the low-lying flat South Forty-Foot Drain valley floor.
- The groundwater catchment is larger than the surface water catchment and includes a number of dry valleys on top of the Lincolnshire Edge.
- Geology and hydrogeology - the area can be divided into four distinct geological bands:
  - Upper Catchment - the Lincolnshire Limestone - a principal aquifer.
  - Mid Catchment - the Kellaway Beds and Great Oolite group - a band of thin units with very variable permeability from very high to very low.
  - Low Catchment - the Oxford Clays - a low permeability aquitard, overlain in parts with till and some small areas of higher permeability glaciofluvial sands and gravels.
  - South Forty-Foot Drain floodplain - very flat area underlain with tidal flat and peaty deposits.
- The following are key controls on the surface water-groundwater interaction:
  - The position of the bedrock water table. When the Lincolnshire Limestone water table is high this supports the flow in the headwater streams and the water table in the Great Oolite and Kellaway Beds. When it is low, the streams lose water to ground and can dry out in reaches.
  - The permeability of the underlying bedrock. Where permeability is low, losses and gains from the rivers to groundwater are limited
  - The nature of the streambed material. Where present lower permeability alluvial bands can reduce leakage, however artificial deepening of channels increases leakage.
- Peat wastage - in the South Forty-Foot valley floor, artificial drainage has led to drying and wastage of the peat.

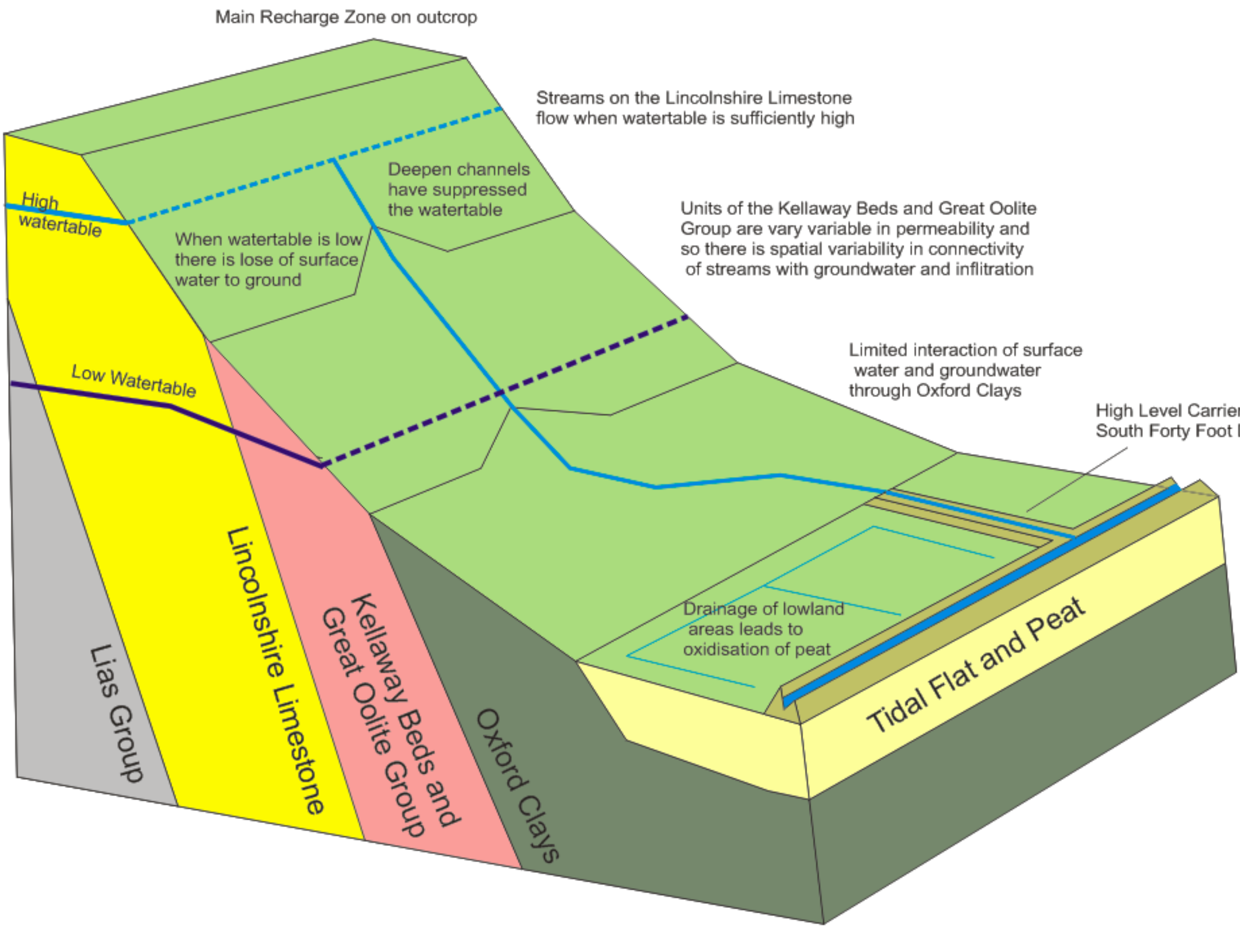


Figure 6-1: South Forty-Foot Conceptual Model

A wide suite of WWNP interventions are possible across the catchment including land-use and soil management practices which promote infiltration and limit run-off generation. The diagram below however focuses on interventions types that are specific to the hydrogeological conditions of the AoI. They cover restoring the headwater streams, the location of run-off attenuation features to maximise infiltration benefits and the mitigation of peat loss. The groundwater vulnerability of the Lincolnshire limestone in parts of the area is high and so the implementation of measures should consider this constraint. Mitigation could take the form of changes to land use and agricultural practices in the immediate area.

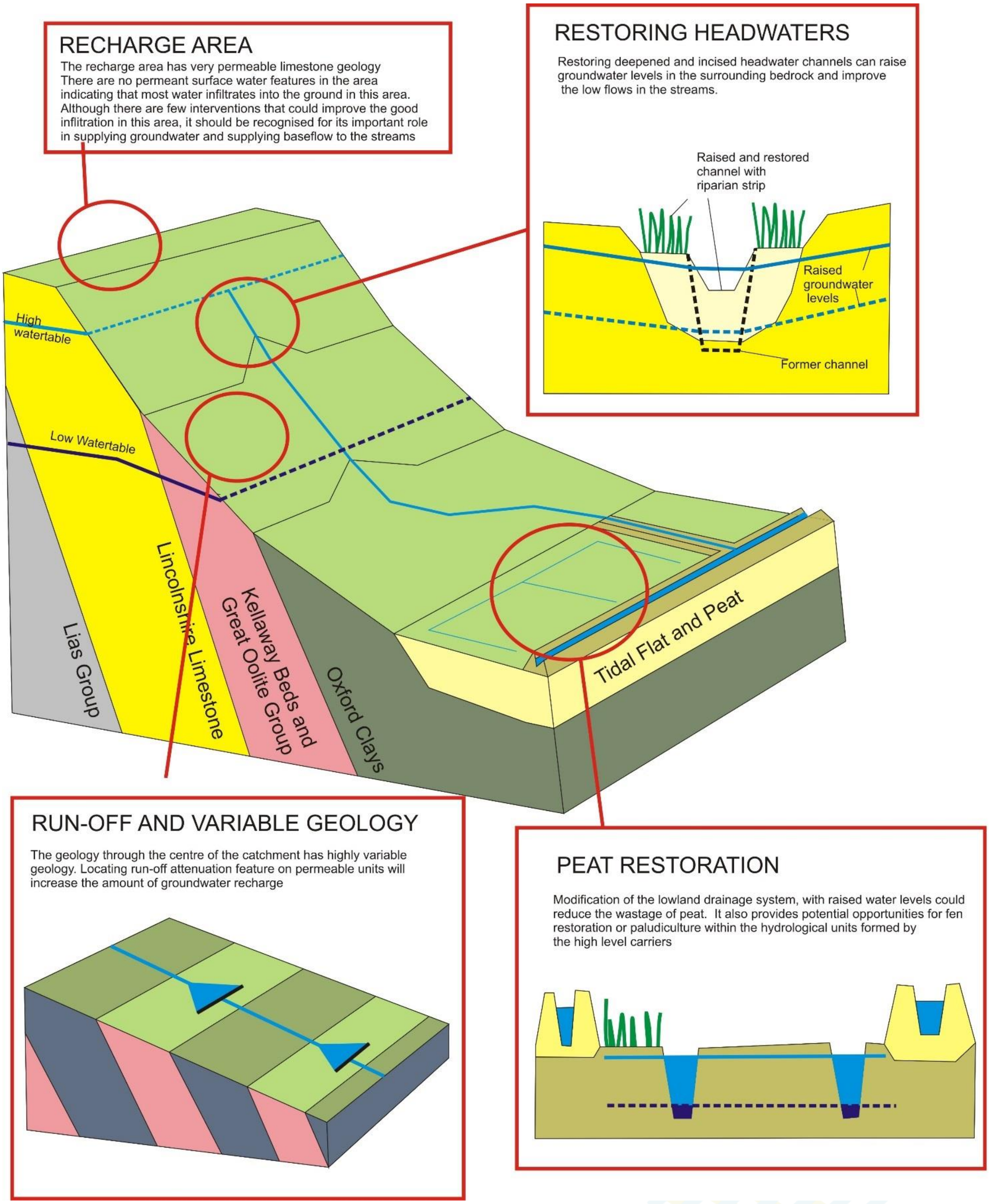


Figure 6-2: South Forty-Foot Conceptual Model incorporating WWNP Measures

7 Conceptual Model and WWNP Potential Key Summary: Cam and Ely Ouse

The following section summarises the key findings from the Cam and Ely Ouse AoI. Further information on this catchment including details from the site visit, local stakeholder engagement and potential WWNP measures can be found within its catchment-specific report.

The hydrogeological conceptual model is shown in Figure 7-1 and Figure 7-2. It has the following features:

- Topography:
  - The area is dominated by a large plateau area at around 30-40mAOD.
  - The Little Ouse valley cuts through the plateau to around 5mAOD, with dry valleys that cut between the two levels.
- Geology and hydrogeology:
  - The whole area is underlain by the chalk which forms a principal aquifer.
  - The overlying cover sands allow recharge through to the Chalk.
  - The valley is lined and underlain with sand and gravel deposits, overlying these are peat and alluvial deposits.
- Groundwater discharges:
  - The Little Ouse is the only large permanent surface water feature in the AoI and is an expression of the regional water table. This regional groundwater level maintains the water table within the valley floor peats
  - A number of dry valleys cross the area. There is limited run-off in these features due to the high infiltration rate.
  - Seepage faces occur on the edge of the valley floor. These have been disrupted by catchwater drains which reduce the extent of wetland habitats dependent on seepages.
- The Little Ouse is navigable, and the weirs mean that sections of the river have levels at or above the local floodplain and nearby groundwater levels. This means that drains on the floodplain form an important role in removing surface water and suppressing the water table.
- The water budget of the area has been significantly changed by forestry plantations. The area of coniferous woodland, which covers a large proportion of the AoI, has a negative water budget in average years.

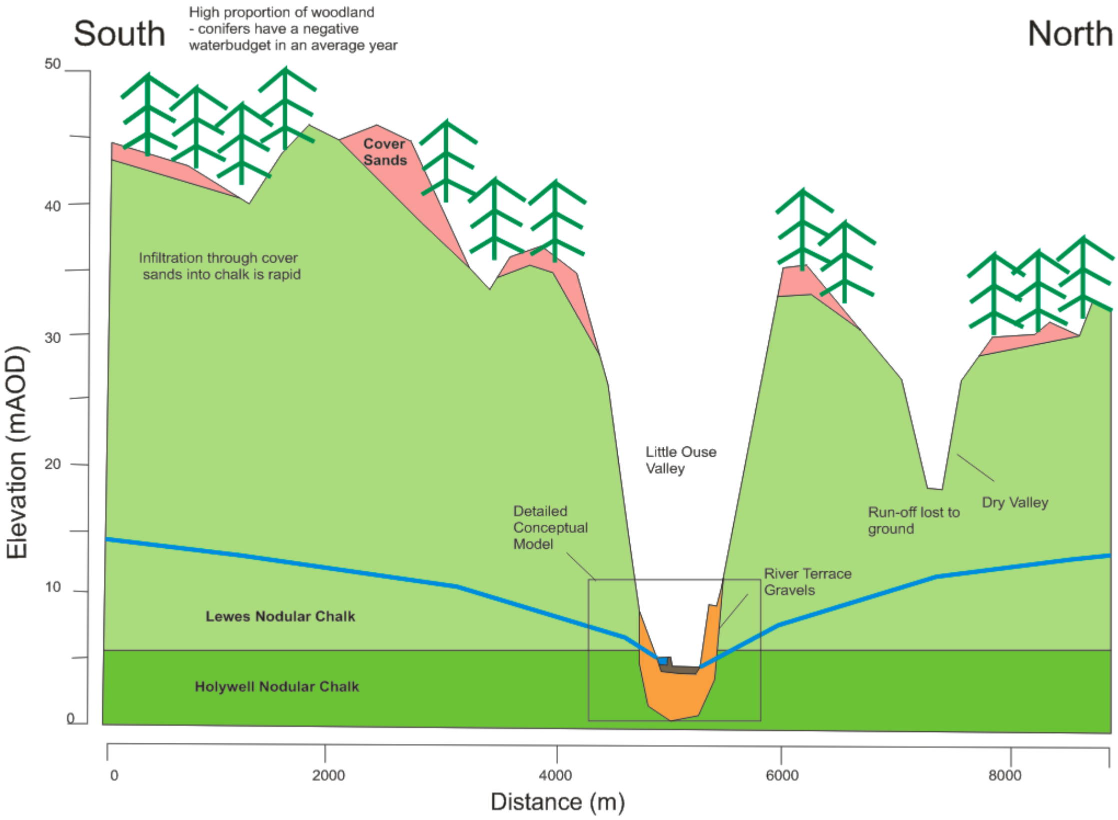


Figure 7-1: Cam and Ely Ouse AoI Conceptual Model

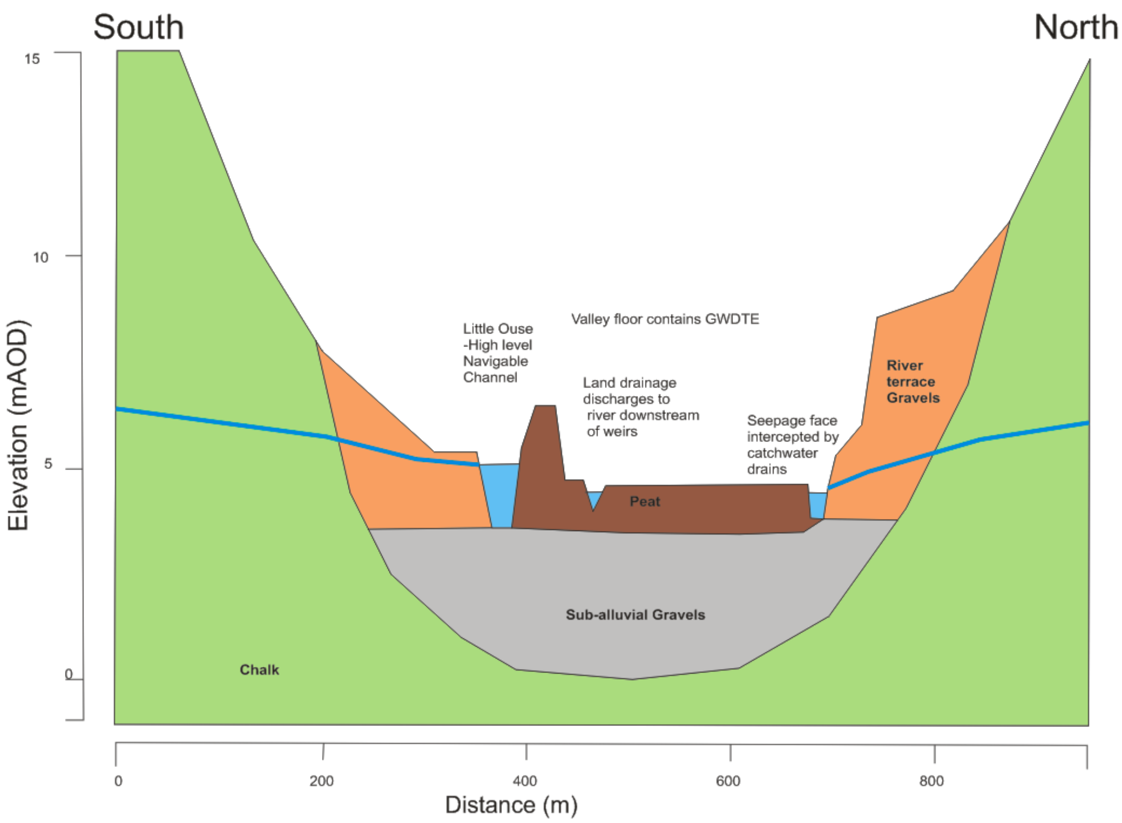


Figure 7-2: Cam and Ely Ouse Valley Conceptual Model

The very high infiltration rates means that a number of WWNP that would be effective in other locations such as run-off attenuation features or the improvement of soil structure are not likely to be so effective in this area. The study has identified two main areas for interventions:

- Modifying the land-cover of the area to improve the water budget. In the main, this would involve reducing the coverage of conifers across the area.
- In areas where the water table lies close to the surface:
  - Removal of catchwaters on the valley sides and restoration of habitats dependent on seepage faces.
  - Removal of woodland in these specific areas, as their root systems which can tap the water table, can continue to transpire at higher rates into dry periods.

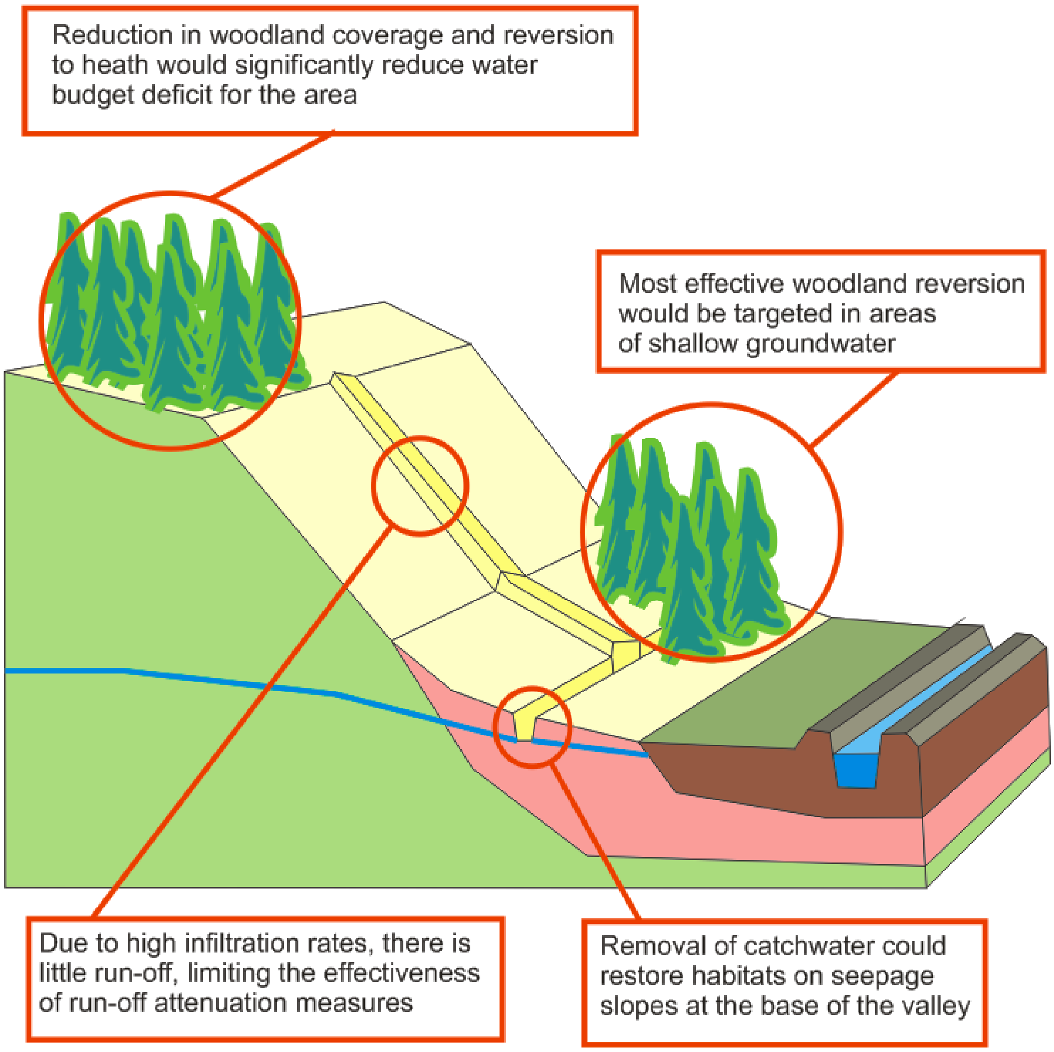


Figure 7-3: Cam and Ely Ouse Conceptual Model with WWNP Measures

8 Conceptual Model and WWNP Potential Key Summary: East Suffolk

The following section summarises the key findings from the East Suffolk AoI. Further information on this catchment including details from the site visit, local stakeholder engagement and potential WWNP measures can be found within its catchment-specific report.

The hydrogeological conceptual model is shown in Figure 8-1. It has the following features:

- Topography:
    - The area is dominated by a large plateau area at around 60-80mAOD.
    - The Gipping valley cuts through the plateau to around 20mAOD, with its tributaries forming valleys that cut between the two levels.
- Geology and hydrogeology:
    - The whole area is underlain by the chalk which forms a principal aquifer.
    - The overlying Crag is limited in extent and depth and therefore it has a limited role.
    - The hills are overlain by Lowestoft Till. This only allows limited recharge to the underlying chalk.
    - Various sand and gravel formations occupy the area and are formed of two main groups:
        - Those that underlie the till, which play a limited role other than to allow infiltration through and run-off from the till to reach the chalk.
        - The deposits of the Gipping valley floor which have been subject to extraction.
    - Streams and the River Gipping – there are four main hydrogeological/hydrological settings for streams in the area:
        - Ephemeral streams on the till, with limited baseflow input that flow in wet periods.
        - Losing streams on the chalk and gravel deposits. This is where streams that start on the till, when they reach the more permeable deposits lose water to ground where the chalk water table is at depth
        - Gaining streams on chalk and gravel deposits. These are lower down the system and gain water from the bedrock and superficial aquifers. The valley floors here can have peaty deposits which formed due to the historic high water level.
        - The Gipping - there is variation in the connectivity of the water levels in the Gipping, with the sands and gravels and the extraction lakes within the valley floor, due to variation in bed sediment conductivity.

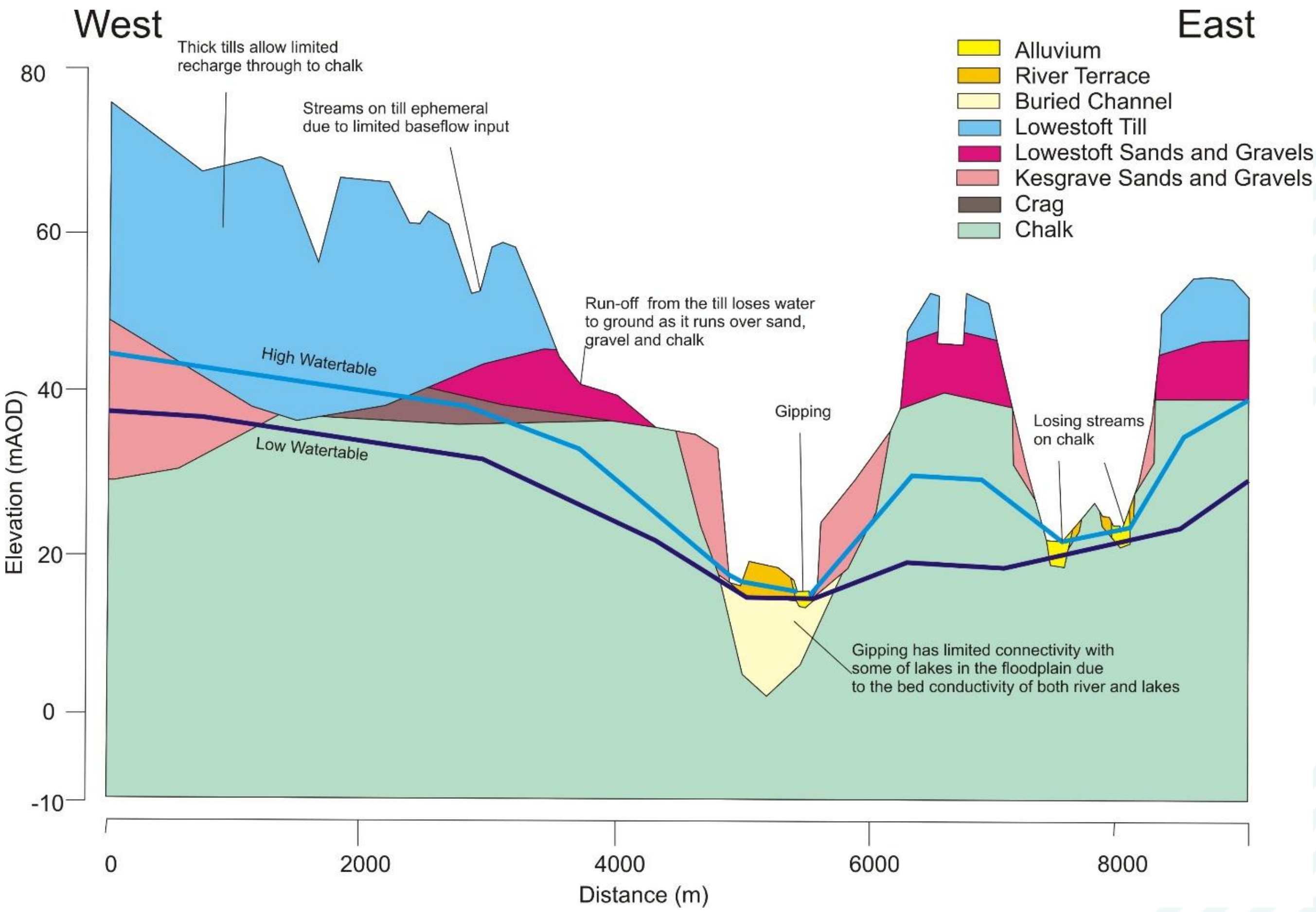


Figure 8-1: East Suffolk AoI Conceptual Model

A wide suite of WWNP interventions are possible across catchments including land use and soil management practises which promote infiltration and limit run-off generation.

Figure 8-2 provides a summary of intervention types that are specific to the hydrogeological controls of the AoI identified through the site visit and baseline assessments. The visit identified four main themes:

- Improving infiltration on the till soils that dominate the plateau. This mainly focused on soil management techniques and roughness strips within fields.
- Run-off attenuation features on permeable deposits on the edge of the till.
- Improving resilience of streams to low groundwater levels in the chalk by renaturalising the channel and storing more water within the valley floors through riparian restoration.
- Managing storage of water in the lake systems of the valley floors.

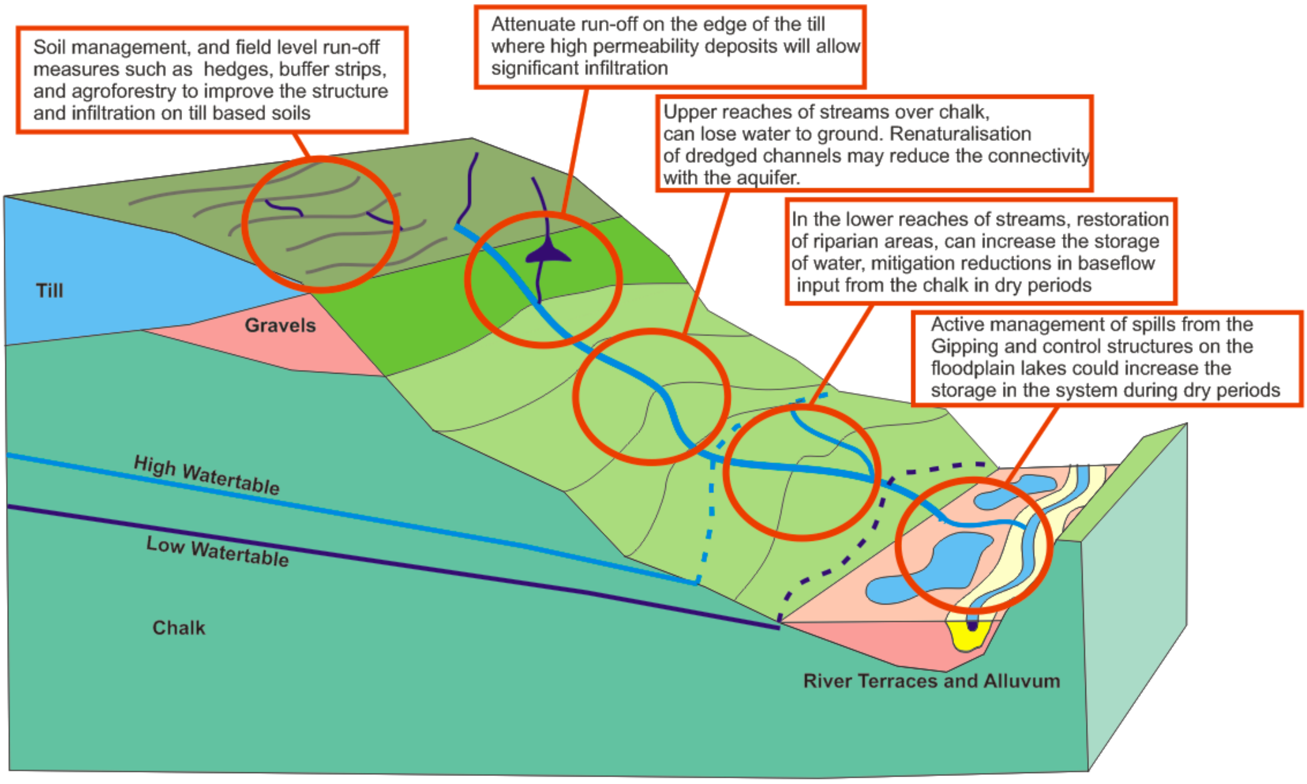


Figure 8-2: East Suffolk AoI Conceptual Model with WWNP Measures

9 Conceptual Model and WWNP Potential Key Summary: Arun and Western Streams

The following section summarises the key findings from the Arun and Western Streams AoI. Further information on this catchment including details from the site visit, local stakeholder engagement and potential WWNP measures can be found within its catchment-specific report.

Overall the AoI is characterised as follows (see Figure 9-1):

- Principal Chalk aquifer across the southern half of the AoI. This supports baseflow to streams draining southward on the south facing slopes of the South Downs. This is essentially a chalk aquifer area with high variation seasonally in groundwater levels. There is some chalk with flints which may have variable impact on recharge, depending on whether it is disturbed or retains solution permeability features. Dry weather cracking of the surface may allow summer bypass recharge.
- To the north of the South Downs groundwater flow within the chalk is northwards through the Upper Greensand to discharge as springs along the edge of the Gault Clay outcrop.
- The Lower Greensand is characterised by interbedded aquifers and lower permeability horizons. As such there may be multiple spring lines. The northern lower Hythe beds have both intergranular and fracture permeability. The Folkestone beds have mainly intergranular permeability. Overall groundwater levels vary little in the Greensand aquifer with possibly only 1m seasonal change in groundwater levels. Whilst the two main aquifers are separated by the Sandgate beds these do contain some sandstones, separated by clays. These form a limited aquitard. However, the Hythe and Folkestone beds often have similar groundwater levels, suggesting that at a regional scale the Sandgate beds do not form an effective groundwater barrier.
- There are some limited superficial deposits within the AoI however, most of these have some level of permeability and are classified as aquifers. They will form an extension of the underlying secondary aquifers. The exception is the Clay with Flints which although classified as unproductive strata may in fact allow significant recharge, depending upon its structure.
- Where the superficial strata, such as permeable head and highly permeable river terrace gravels overlie lower permeability bedrock strata then the superficial deposits have the potential to move recharge horizontally as interflow so as to infiltrate in the next permeable aquifer layer. There are very limited superficial deposits overlying the Gault Clay, with the exception of limited head and alluvium deposits along water courses. However, there are more extensive superficial deposits overlying the Lower Greensand where they may allow interflow over the lower permeability Sandgate horizons.

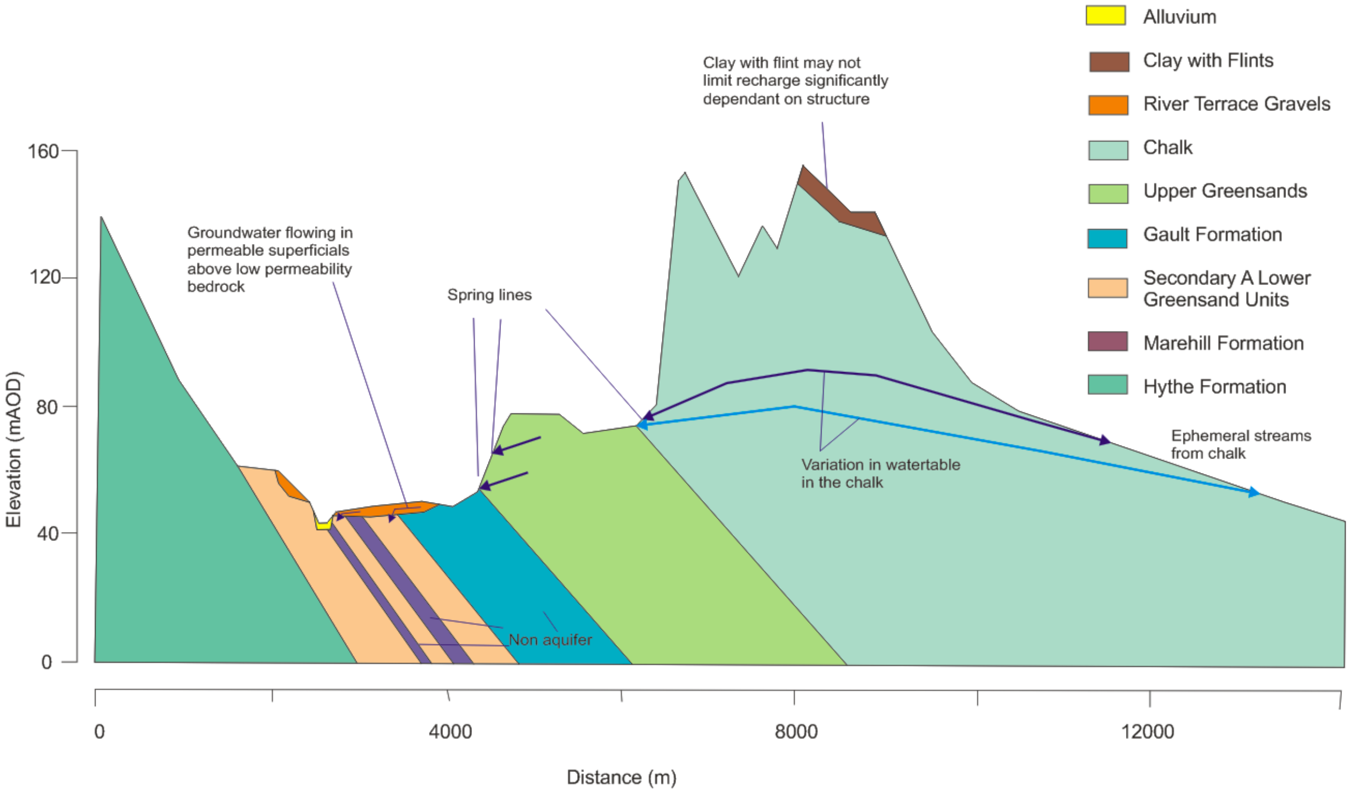


Figure 9-1: Arun & Western Streams Conceptual Model

The area has the following potential for working with natural processes and groundwater:

1 Increase in recharge overlying the permeable strata through land management to promote recharge – this comprises all the AoI except the Gault Clay and the clay horizons within the Sandgate beds. The chalk aquifer outcrop already has a very high level of infiltration with limited runoff, but there may be scope in the areas of clay with flints to slow down runoff and increase infiltration. Increased slower infiltration through clay with flints would result in a longer slower recharge pathway to the underlying chalk. Slowing runoff may also have other benefits, such as reducing sediment runoff. Land management measures would include the following:

a) Measures to increase roughness such as:
   - Cover crops or grass seeding to limit winter runoff and sediment generation.
   - Contour working fields so as to limit rapid runoff pathways.
   - Agroforestry or selective hedging/tree planning to limit rapid runoff.

b) Measures to limit or treat soil compaction potentially including:
   - Minimum tillage to improve soil structure and infiltration capacity.
   - For sandy soils sub-soiling may break up compacted layers but would also disturb soil structure.

2 Runoff attenuation features to increase infiltration in the permeable areas. There is potentially scope for re-infiltration of spring water once it has flowed over the low permeability Gault clay (and to a lesser extent springs originating at the boundary with the Sandgate clays). This mechanism would be more effective when groundwater levels are lower, such as following a dry period. Site specific information would be required to determine where there is sufficient unsaturated zone to facilitate additional recharge. It is noted that due to the very high

intergranular storage in the sandstones, considerable storage may be provided by a fairly limited unsaturated zone thickness.

3 The chalk outcrop area is far from the coastal discharge and also has a significant unsaturated zone. Although infiltration is likely to already be significant (with most net rainfall infiltrating), there may be potential for increasing infiltration through land management and also attenuating runoff at the edges of the Clay-with-flints. Recharge at the top of the South Downs is likely to have a longer lag time than recharge in lower areas. It is therefore more likely to benefit low flows during the summer. Recharge through the clay with flints would take even longer and so smooth the recharge peak.

4 The Greensand aquifers have water tables that in some areas are likely to be close to the surface, especially near to rivers (which are typically gaining). However, given the limited variation in groundwater seasonally, there may be potential for professional expertise to investigate raising incised river channels increasing the height of the groundwater discharge boundary that the rivers form.

5 The area mainly has upland streams with few mature rivers. The exception is the River Rother through Petersfield and downstream which has a wider river valley. There could be potential for floodplain reconnection in the River Rother valley and larger tributaries, and the River Ems between Stoughton and Walderton.

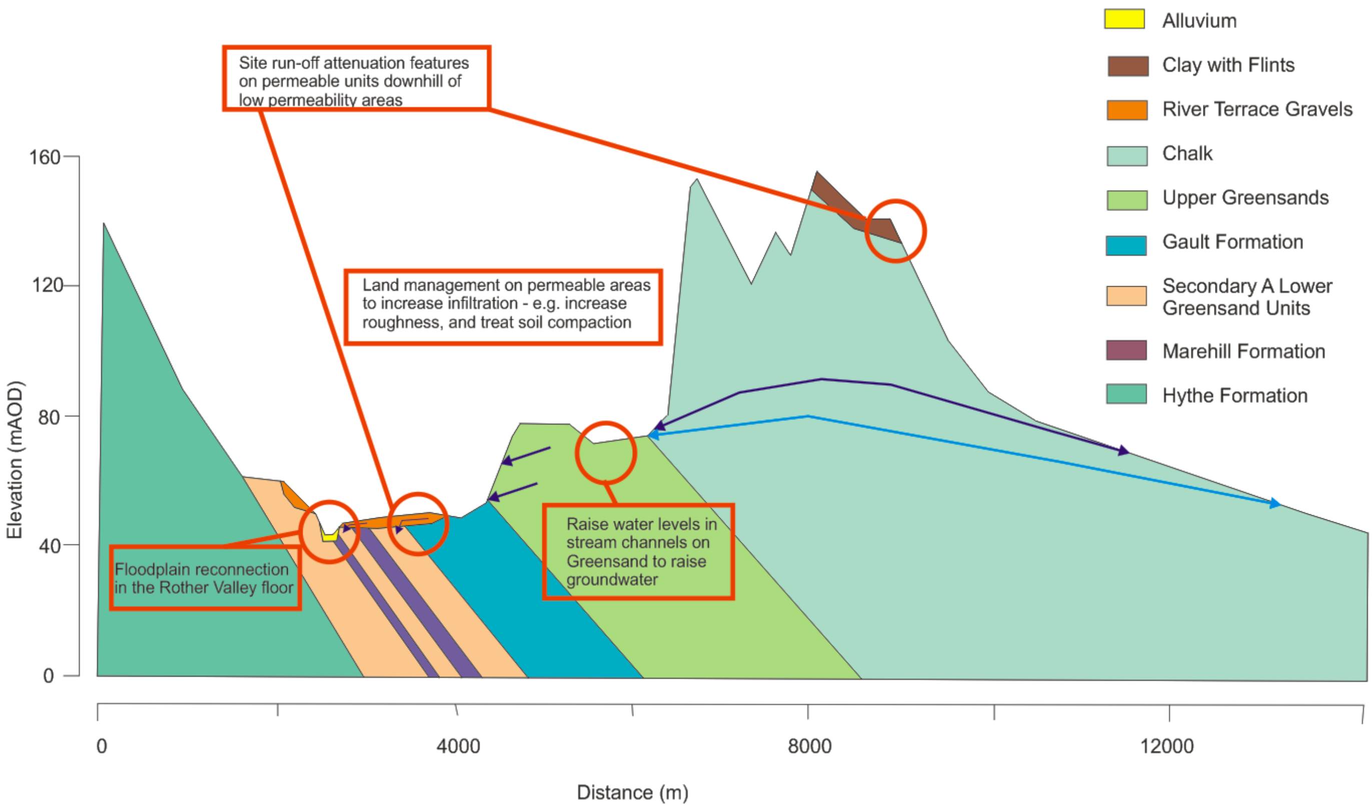


Figure 9-2: Arun and Western Streams AoI Conceptual Model with WWNP Measures

10 Conceptual Model and WWNP Potential Area Key Summary: Otter

The following section summarises the key findings from the Otter AoI. Further information on this catchment including details from the site visit, local stakeholder engagement and potential WWNP measures can be found within its catchment-specific report.

The conceptual model has the following features (west to east):

- The west of the AoI along the edge of the Otter valley includes small outcrops of the Chester Formation which comprises a thin but highly permeable aquifer, cut by faults. The groundwater level is close to the surface and likely to be in connection with river terrace gravels. Enhanced recharge in this area may result in increased groundwater flow towards the main Helsby Sandstone in the Otter valley.
- The main Otter valley is underlain by the Helsby Sandstone (Sherwood sandstone) aquifer. The groundwater level is likely to be in connection with the River Otter but below the level of some of the more minor tributaries. This leaves the potential for leakage from the tributaries to contribute to groundwater recharge.
- The Sidmouth Mudstone (Mercia Mudstone Group) has only limited potential for enhancing groundwater recharge. But measures to increase recharge over the Sidmouth Mudstone may result in increased interflow within the soil and weathered upper margin of the mudstone. This interflow may flow horizontally to nearby surface waters or recharge the Helsby Sandstone in the Otter valley.
- Recharge through the clay caps on the Upper Greensand is likely to contribute to groundwater flow east away from the Otter valley.

A wide suite of WWNP interventions are possible across the catchment including land use and soil management practices which promote infiltration and limit run-off generation. The diagram below however focuses on interventions that are specific to the hydrogeological conditions of the AoI identified through the baseline development and site visit work. Particular interventions relevant in the AoI are (west to east):

- Slowing runoff pathways in the west over the thin Chester Formation bedrock to increase recharge. At times of high groundwater levels the potential for recharge into the Chester Formation may be limited.
- There is likely to be scope for recharge to the margins of the Helsby Sandstone at the west and eastern margins of the Otter valley as the groundwater level is lower. This recharge can be from slower runoff and also infiltration recharge from losing watercourses perched over the sandstone.
- Improving floodplain connectivity in the Otter valley. This will allow increased aquifer storage in the floodplain and associated alluvial aquifer.
- Slowing runoff in east of the AoI will result in increased recharge through the clay caps and increased recharge to soils over the Sidmouth Mudstone. Recharge to the clay caps will benefit the Upper Greensand. Recharge over the Sidmouth Mudstone is likely to form interflow which will discharge slower to nearby surface waters and also have the potential to recharge the Helsby Sandstone.
- The northern and eastern part of the part of the AoI is substantially underlain by the Sidmouth Mudstone. These areas have heavy mudstone soils and are often used for animal-based agriculture, such as dairy farming. Soils may become compacted and in poor condition. There are water quality and sediment issues. Slowing down runoff in these areas may improve interflow along the base of the soil/weathered top of the mudstone and allow more infiltration at the edge of the

more permeable sandstones. There may also be water quality and sediment benefits from improved soil management and infiltration.

- The eastern part of the north of the AoI is underlain by sandstone, and mainly used for arable farming. It is more faulted than further south and faults may locally fragment the aquifer. There is nevertheless potential for increasing recharge through the base of streams by slowing quickflow, which would have benefits for baseflow within the Otter valley.

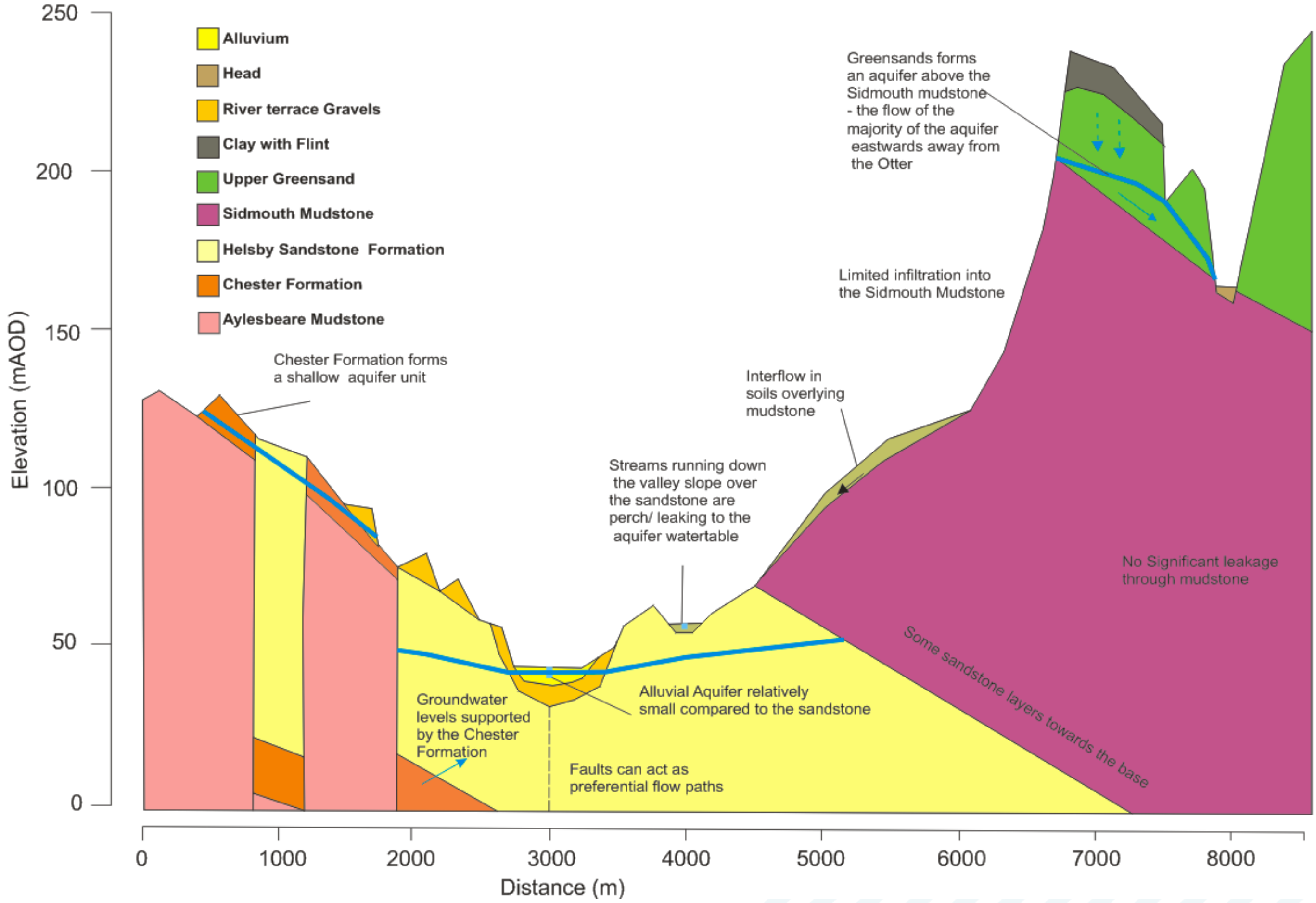


Figure 10-1: Otter AoI Conceptual Model

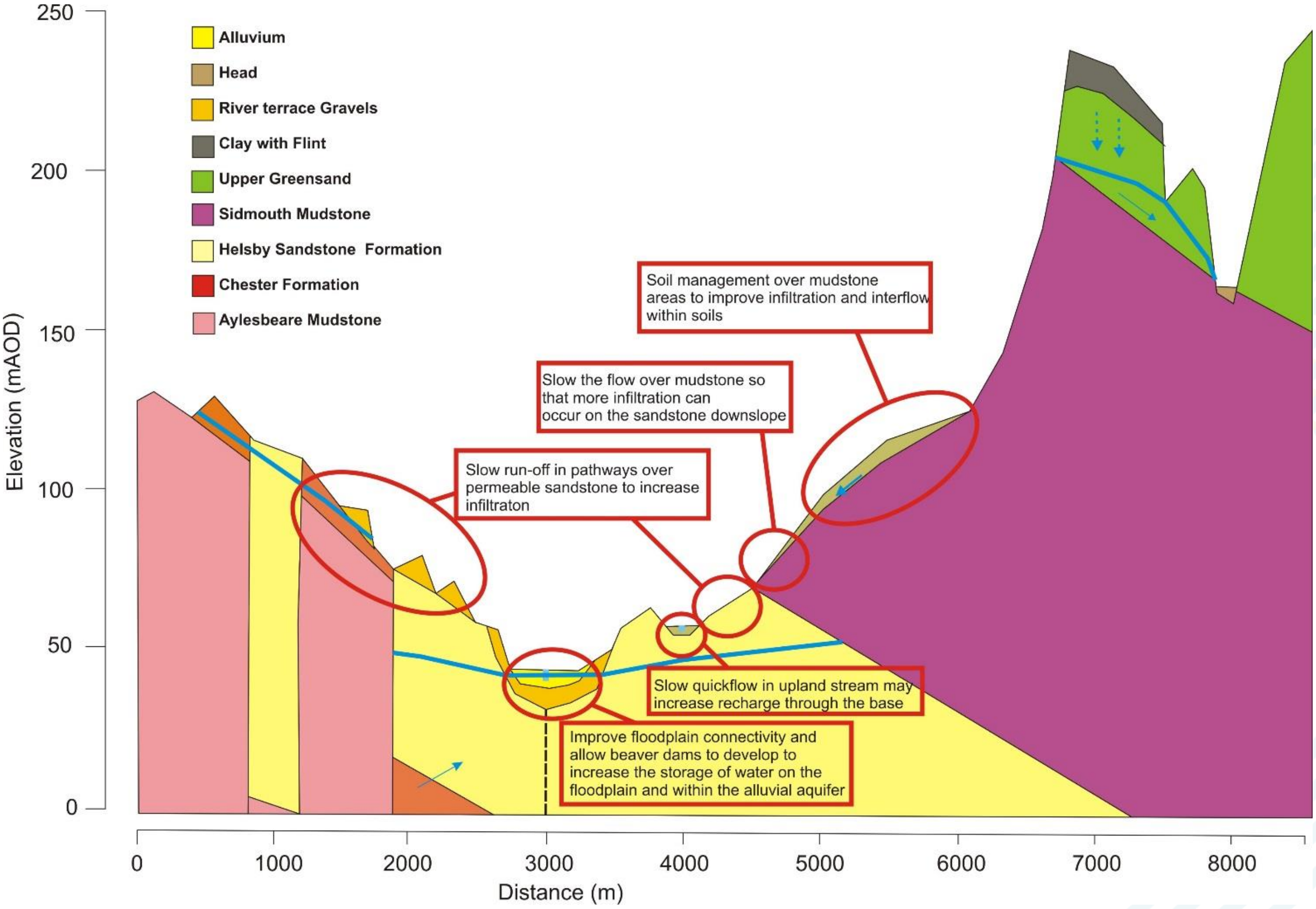


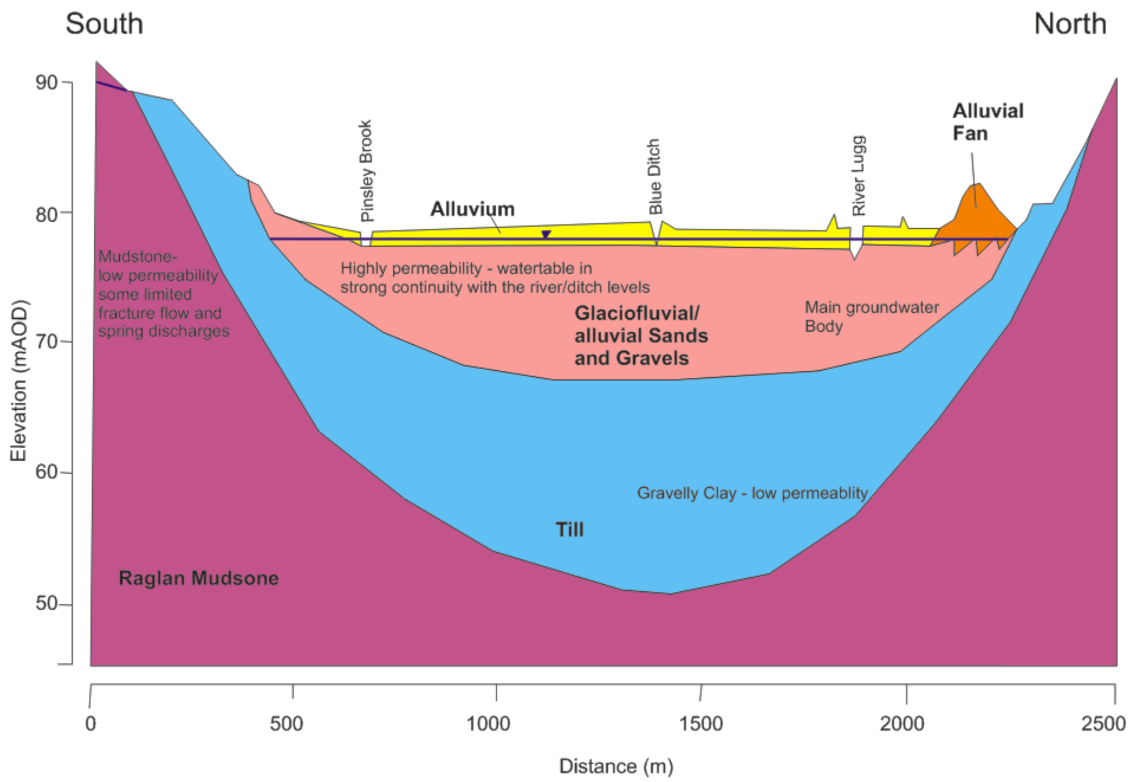
Figure 10-2: Otter Conceptual Model with WWNP Measures

11 Conceptual Model and WWNP Potential Area Key Summary: Wye

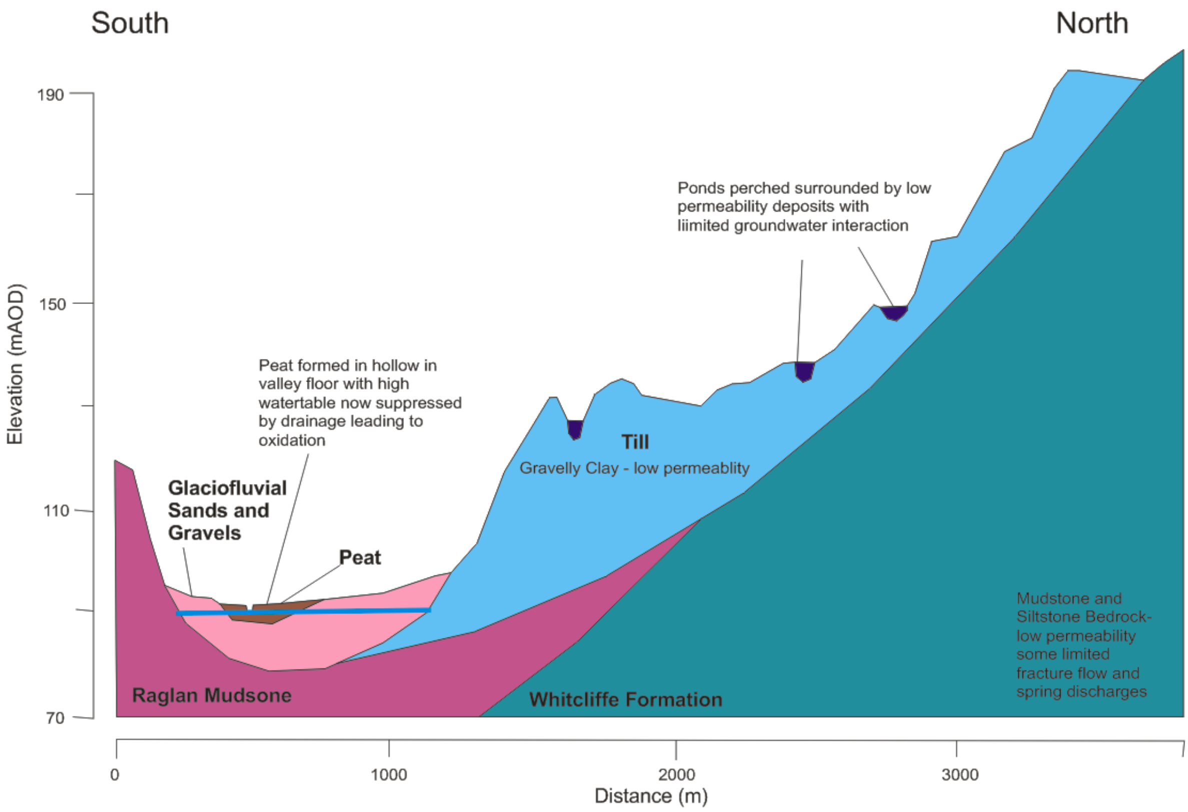
The following section summarises the key findings from the Wye AoI. Further information on this catchment including details from the site visit, local stakeholder engagement and potential WWNP measures can be found within its catchment-specific report.

The conceptual model of the area is presented in two cross sections (Figure 11-1). The first presents a cross section of the Lugg floodplain between Kingsland and Eyton. The second is a line from the valley floor at Shobdon Marsh and through the uplands to the north. They show the following features:

- Bedrock:
  - The area is underlain, in the main, by low permeability Mudstones and Siltstones. There is some limited flow through fractures with spring discharges.
- Till covers parts of the hillside and underlies parts of the valley floors. Perched ponds and streams form in topographical hollows, with limited groundwater interaction.
- Thick high permeability glaciofluvial sands and gravels underlie the main valley floors. These are dominated by intergranular flow.
  - The height of the water table within them is controlled by the stage of the watercourses. The stages have been artificially influenced by weirs, drainage works and abstractions. A number of these weirs are now in the process of removal focused on the benefits this may have on flood risk and biodiversity.
  - When water is higher in the watercourse than the surrounding sands and gravels, the watercourses lose water.
- Peat formed in a topographical hollow within the glacio-fluvial deposits which created an area with a high water table that allowed peat to accumulate. The straightening of Pinsley Brook will have lowered the water table in the area.



At Kingsland



At Shobdon Marsh

Figure 11-1: Wye/River Lugg AoI Conceptual Models

A wide suite of WWNP interventions are possible across the catchment including land-use and soil management practices which promote infiltration and limit run-off generation. The diagram below however focuses on intervention types that are specific to the hydrogeological conditions of the AoI. They cover options for the floor of the valley underlain by the alluvial aquifer and options for the surrounding hills.

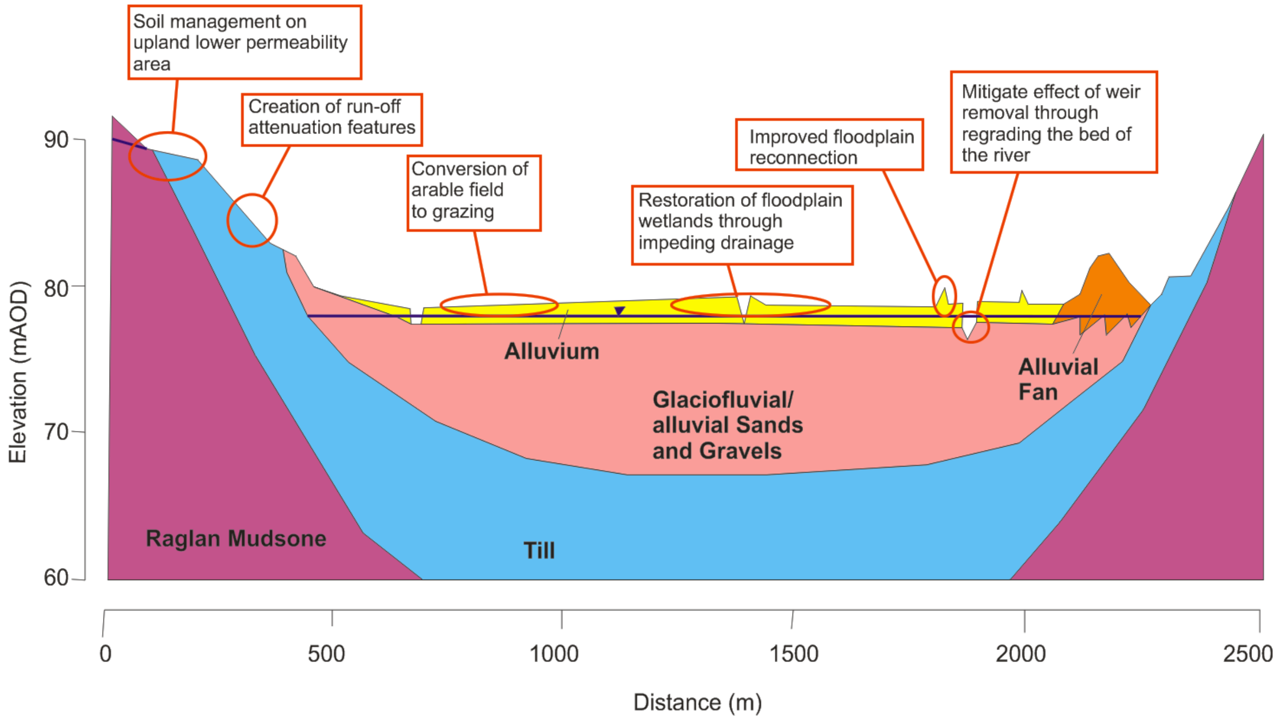


Figure 11-2: Wye/River Lugg AoI Conceptual Model with WWNP Measures

12 Conceptual Model and WWNP Potential Area Key Summary: Alt Crossens

The following section summarises the key findings from the Alt Crossens AoI. Further information on this catchment including details from the site visit, local stakeholder engagement and potential WWNP measures can be found within its catchment-specific report.

The hydrogeological conceptual model is shown in Figure 12-1. It has the following features:

- Topography:
  - A ridge from Ormskirk to Skelmersdale lies in the centre of the area at circa 60mAOD. The ground falls to the north, south and west from this ridge to the coastal plain.
- Bedrock geology and hydrogeology:
  - The Sherwood Sandstone Principal Aquifer outcrops over the majority of the AoI; and is confined beneath a wedge of the Mercia Mudstone in the north and west of the area.
  - The eastern boundary of the AoI is formed by a fault with the Lower Coal Measures juxtaposed against the Sherwood Sandstone. There is some groundwater flow across this fault into the Sherwood Sandstone.
  - Broadly groundwater flow follows topography, however this has been modified by abstractions which have supressed the water table.
- Superficial Geology and Recharge:
  - The superficial sediments overlying the Sherwood Sandstones mainly consist of glacio-aeolian sands and till.
  - The till can underlie the glacio-aeolian sands and restrict recharge to the sandstone in these areas. But the effect of the till is limited where it is thin.
- Streams and groundwater – streams lie in three broad hydrogeological situations:
    - Contained within thick till with limited groundwater interactions;
    - Contained or fed by perched sand aquifers;
    - Within the Sherwood Sandstone groundwater discharge zone within sand deposits.

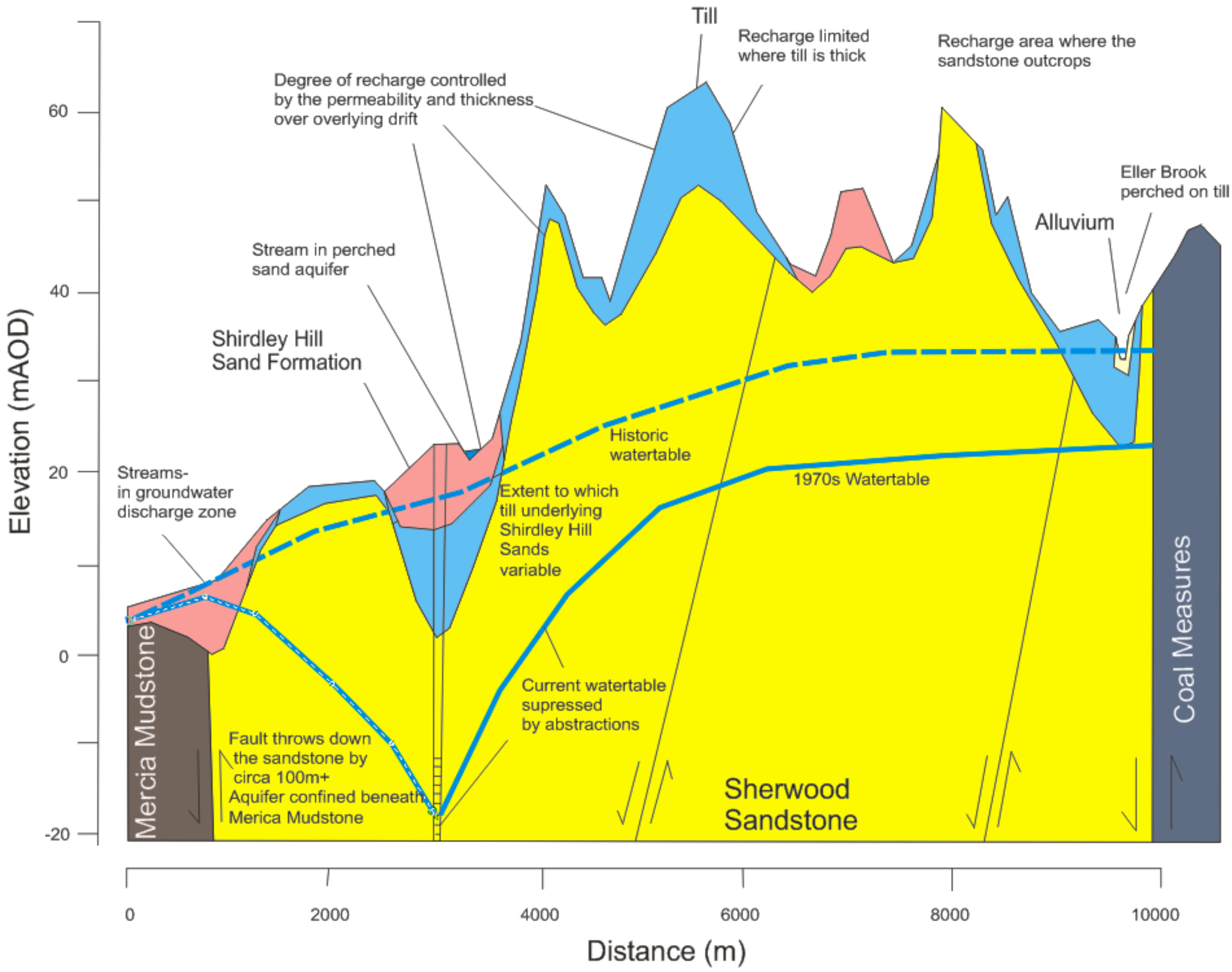


Figure 12-1: Alt Crossens AoI Conceptual Model approximately W-E

The site walk-over and conceptual model identified the following areas where WWNP inventions could be implemented:

- Improved soil management to reduce compaction issues, especially in areas of till.
- Targeting runoff attenuation features to slow the flow in areas where till does not cover the surface or underlies the Shirdley Hill Sand Formation, so water can more readily recharge the Sherwood Sandstone.
- Restore the eco-hydrological conditions of groundwater dependent terrestrial ecosystems in the area such as Martin Mere.

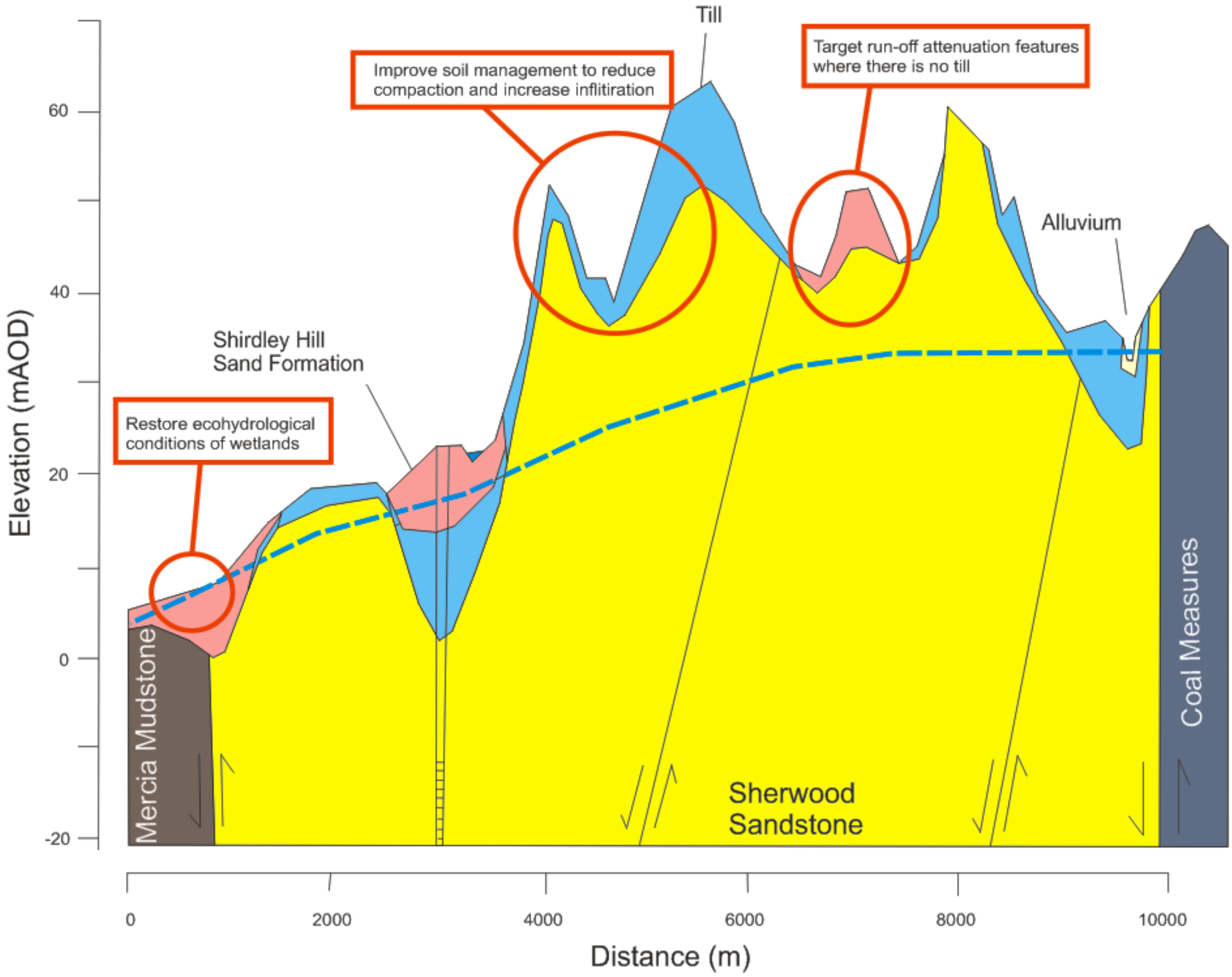


Figure 12-2: Alt Crossens Conceptual Model with WWNP Measures

13 Conceptual Model and WWNP Potential Key Summary: Brue

The following section summarises the key findings from the Brue AoI. Further information on this catchment including details from the site visit, local stakeholder engagement and potential WWNP measures can be found within its catchment-specific report.

The conceptual model of the area is shown in Figure 13-1 and can be summarised as follows.

- Topography:
  - The area slopes westward overall, and ground elevations fall by up to 200m in 9km to the western edge of the AoI.
  - The catchment features three main valleys: the River Alham valley in the north, which drains towards the south-west; River Brue valley in the centre, also draining south-west; and River Pitt valley in the south, draining toward the north-west.
- The AoI groundwater catchment is greater than the surface water catchment. Consequently there are two main dry valley areas, which lie in a different surface water catchment but may provide groundwater to the Brue catchment.
- Geology and hydrogeology - the area can be divided into four distinct geological bands:
  - Upper Catchment (eastern boundary of AoI) – Upper Greensand Formation – a high permeability Principal aquifer.
  - Mid-upper Catchment (eastern area surrounding North and South Brewham)- the Oxford Clay Formation and Kellaways Formation – which are mainly low permeability aquitards.
  - Mid-lower Catchment (central thick north-south trending band) – Great Oolite Group, Inferior Oolite and Bridport Sand - a series of high permeability, moderate to very productive aquifers.
    - The Bridport Sands is dominated by intergranular flow whereas the Oolites are primarily fracture flow dominated.
  - Low Catchment (primarily in north-west of AoI) – Lower Lias Group Units - which are low permeability aquitards.
- The following are key controls on the surface water-groundwater interaction:
  - The headwaters are supported by groundwater from the Upper Greensands
  - Where permeability is low (i.e. Oxford Clays and Lias Group), losses and gains from the rivers to groundwater are limited.
  - The position of the bedrock watertable. When the Great Oolite/Inferior Oolite watertable is high this supports the flow in the Alham, Brue and Pitt rivers and their tributaries. When it is low, there is reduced baseflow input into watercourses.
  - The nature of groundwater movement in the aquifers. Intergranular flow dominated aquifers like the Bridport Sands and the Upper Greensand provide a more steady input of baseflow compared to the flashy oolite formations.
- The nature of the streambed material. Where present lower permeability alluvial bands can reduce leakage, however artificial deepening of channels, particularly where this may cut through alluvial deposits, increases leakage.

Figure 13-2 illustrates the potential intervention types that are specific to the hydrogeological conditions of the AoI. Additional discussion of their local applicability is provided in Table 13-1.

Table 13-1: Discussion of Brue AoI Specific Interventions

Measure	Discussion
Run-off Attenuation Features (RAFs)	RAFs will be most effective in enhancing groundwater recharge when targeting high permeability units. Where possible, these should target intergranular flow dominated units such as the Bridport Formation as this provides significant support to the rivers in baseflow conditions. This is in contrast to RAFs on karstic units such as the Cornbrash or Inferior Oolites where rapid flow through the aquifers may mean that they provide more limited baseflow during low flows conditions. However, any increase in recharge is likely to benefit water resources. Thin permeable units in formations like the Kellaway beds also present significant opportunities especially as these units provide baseflow in reaches with limited groundwater input.
Tree Planting	Tree planting should target low permeability units like the Oxford Clay. Trees in these areas will improve soil structure, increase surface roughness and overall increase infiltration. On high permeability units, tree planting should avoid areas with relatively shallow watertables as trees can continue to access water from deeper layers relative to other land-covers such as heathland. An exception to this is riparian and floodplain woodland where the increase surface roughness can attenuate flows leading to greater storage and infiltration. In all cases broadleaf woodland is preferable to coniferous woodland as it has lower water requirements.
Soil Management	Soil management techniques such as minimum tillage, on especially on low permeability soils should be encouraged. Across the catchment low permeability units, such as the Oxford Clay, occupy a significant proportion of the land. Moderate increasing infiltration and interflow in these areas could reduce the flashiness inputs into the river network from these areas, and so could have a significant effect in increasing overall baseflow.
Incised River and Floodplain connectivity	The river floodplains occupy a relatively small part of the catchment, however they can have a role to play. The site visited identified that local rivers and streams had been incised and deepened, so losing floodplain connectivity. River restoration schemes that raise the bed of the water course and therefore the stage of the river, will increase the height of the surrounding watertable. Schemes can also increase floodplain storage and connectivity. Water stored on the floodplain can re-enter the river through groundwater flow paths, having the added benefit of improving water quality in the river.

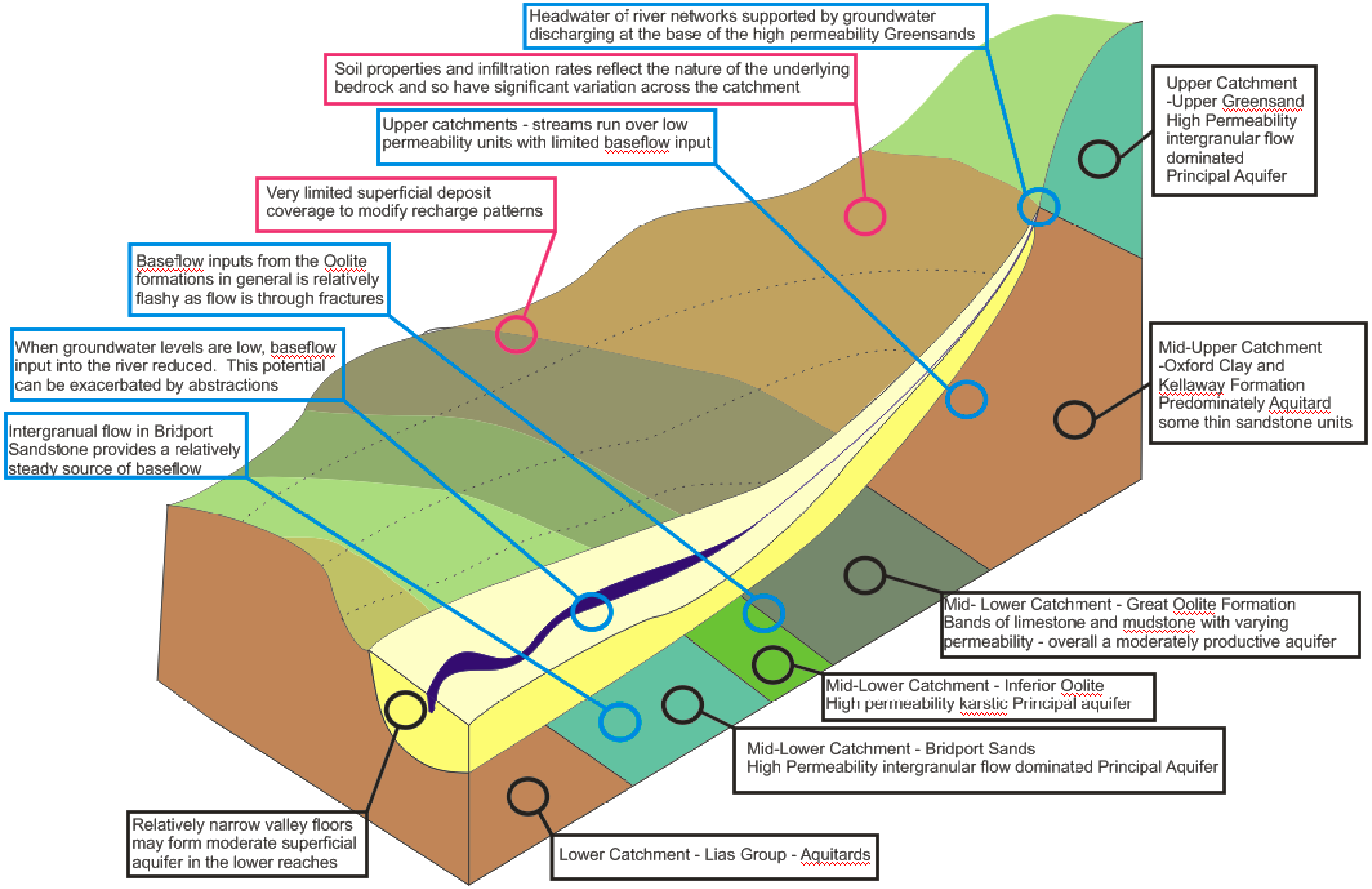


Figure 13-1: Brue AoI Conceptual Model

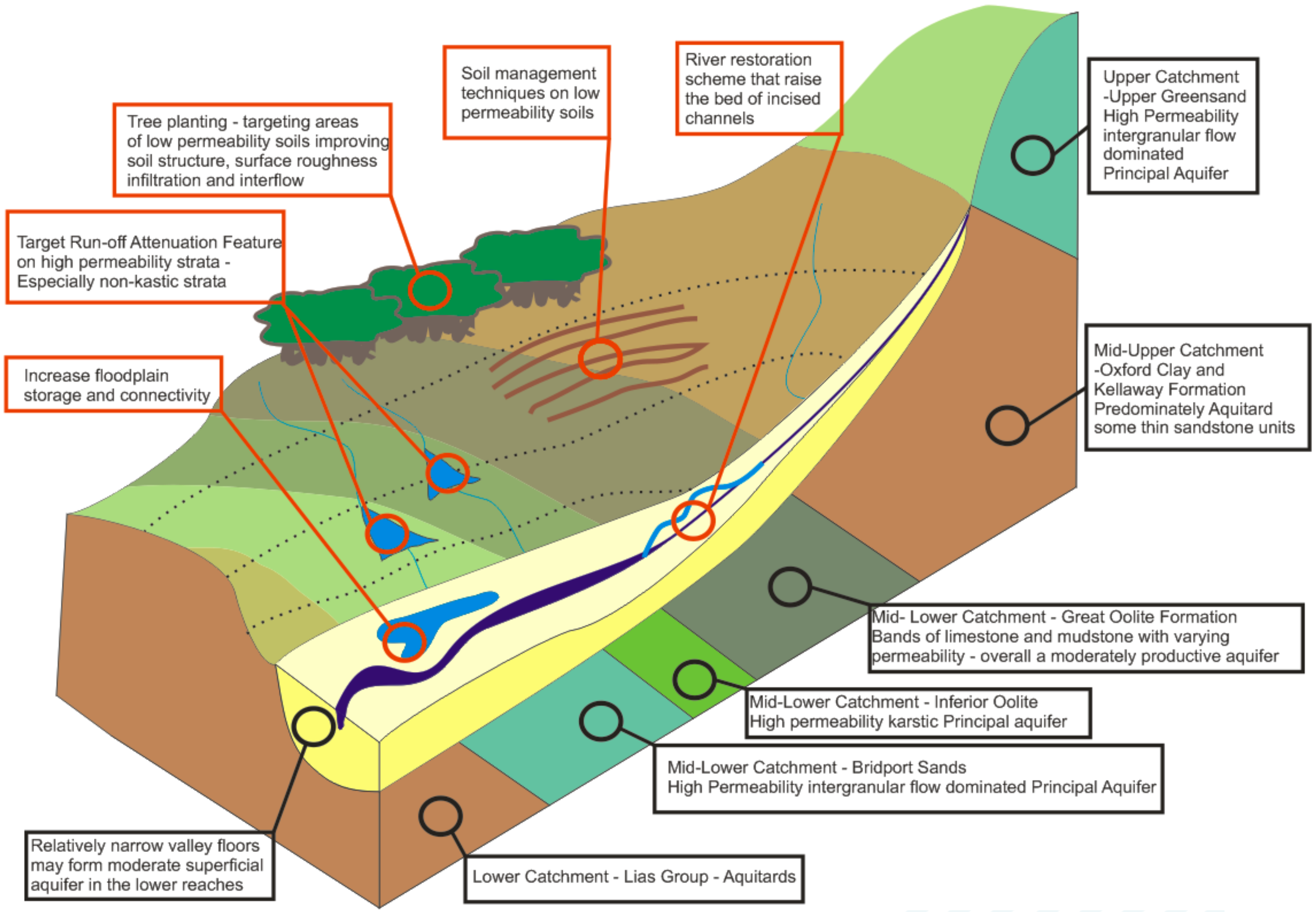


Figure 13-2: Brue AoI Conceptual Model with WWNP Measures

14 Conceptual Model and WWNP Potential Key Summary: Till and Tweed

The following section summarises the key findings from the Till and Tweed AoI. Further information on this catchment including details from the virtual site visit, local stakeholder engagement and potential WWNP measures can be found within its catchment-specific report.

The hydrogeological conceptual model is shown in Figure 14-1 and has the following features:

- Topography – there are two distinct topographical zones:
    - The wide flat valley floor of the Milfield Plain,
    - A ridge along which the Fell Sandstone outcrops. This ridge is bisected in the south by the floodplain of the River Till.
- Geology and hydrogeology:
    - Structure – the bedrock units dip to the east, with the younger Scremerston Formation outcropping in the east, overlying the Fell Sandstone and the Inverclyde Group.
- The Fell Sandstone consists of alternating bands of low permeability mudstone and high permeability sandstone.
- The Scremerston Formation has coal seams which have been worked.
- Superficials – the two main zones of the superficials reflect the topography.
        - In the Milfield Plain is a thick sequence of glacial, lacustrine and alluvial deposits, which includes thick bands of sand, gravels and cobbles, forming a significant superficial aquifer.
        - On the ridge, there is a patchy skim of relatively permeable till, with some pockets of peat and alluvium in topographical lows.
- Infiltration and recharge:
    - On the Fell Sandstone outcrop, interflow and run-off recharge over mudstone units are significant until a sandstone unit is reached and infiltration into the sandstone units can occur.
- Abstractions
    - Abstractions on the Fell Sandstone target the sandstone units. Due to the thin nature of the units, the depth and extent of the drawdown that occurs are significant.
- Groundwater-surface water interactions
    - On the higher ridge, streams that run over sandstone units lose water to ground and are often dry.
    - Lower down on the ridge, sandstone units can form spring lines,
    - Beneath the Milfield Plain, the Fell Sandstone is likely to provide significant groundwater input into the superficial aquifer through gaps in the underlying till.

Figure 14-2 illustrates the potential intervention types that are specific to the hydrogeological conditions of the AoI. Additional discussion of their local applicability is provided in Table 14-1.

Table 14-1: Discussion of Till and Tweed AoI Specific Interventions

Measure	Discussion
Run-off Attenuation Features (RAFs)	RAFs on the Fell Sandstone outcrop are likely to be most effective in increasing groundwater recharge if sited on the sandstone units. However, RAFs on mudstone units also have a role, as the slow release of water from them may increase rates of infiltration as they pass over sandstone units.
Headwater Wetlands	In a similar way to RAFs on mudstone units, the restoration of headwater wetlands is likely to reduce the peakiness of flow from these areas in flood events. This means that infiltration in downstream sections of streams that pass over sandstone units would increase.
Woodland Planting	Woodland planting targeting lower permeability mudstone and superficial deposit areas on the Fell Sandstone, should decrease surface run-off and soil structure leading to greater infiltration and interflow. Planting of woodland is likely to be inappropriate on many peaty or organic rich soils as it could lead to the release of carbon and stop the restoration of UKBAP peatland habitats on the sites.
Scremerston Formation and Minewater	Installations of RAFs and a number of other WWNP on the Scremerston Formation have the potential to increase mine water generation (with associated water quality concerns), especially if located close to mine entries, which are dense along the edge of the formation. Given the limited recharge through the Scremerston Formation to the Fell Sandstone due to the mudstone unit at the top of the Fell Sandstone, working in this area would have limited benefits for water resources.
Regrading River Till	The cessation of dredging of the River Till has led to the widening and shallowing of the river. As the river forms a groundwater discharge boundary and has good hydraulic connectivity with the surrounding superficial aquifer, this has led to a raising of groundwater levels in the floodplain.
Wetland on Milfield Plain	The creation of wetlands on Milfield Plain would require the blocking of the agricultural drainage network. This would raise groundwater levels and groundwater storage in the area, which would increase baseflows to the river. If created in the right place, this baseflow input could help offset abstractions from the river. This would in effect act in a similar way to winter reservoirs which are designed to capture high flows and use the water during periods of water restriction. These wetlands however would not offer the finer level of control of a winter reservoir, as the rate of loss through the ground could not be set. Creating wetlands on the Milfield Plain are likely to be most successful if a whole hydraulic compartment can be restored, as the high permeability deposits mean that external drains can suppress groundwater levels.
Removal of embankments and increased floodplain connectivity on Milfield Plain	A similar measure to the creation of wetlands on the plain, however if this is not accompanied by ditch blocking, the high permeability nature of the superficial deposits, means that the higher groundwater levels created by inundation events are likely to be short lived. The flat nature of the floodplain means that the flood impacts of removing short sections of flood embankment may extend over a significant area.

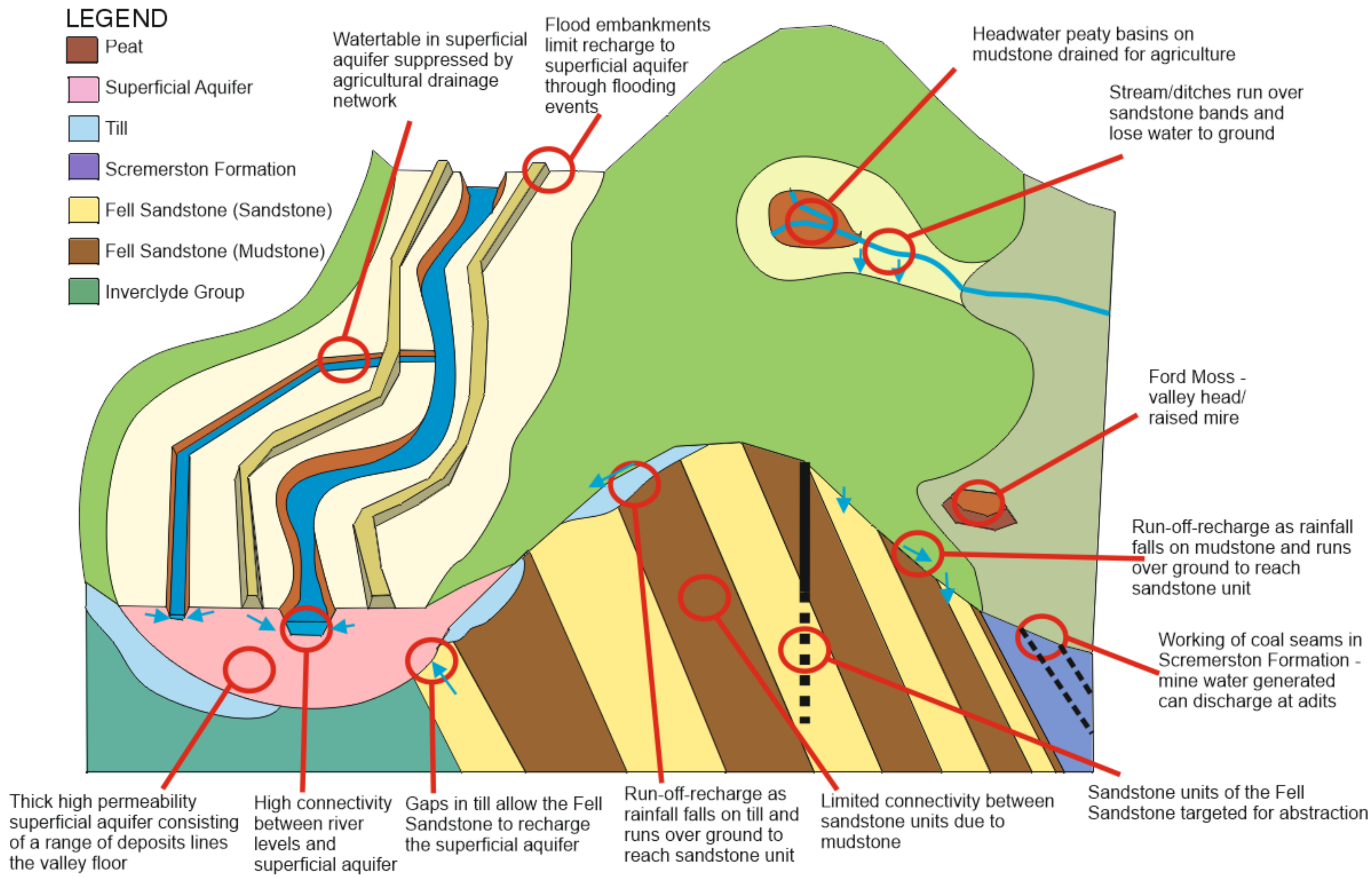


Figure 14-1: Till and Tweed AoI Conceptual Model

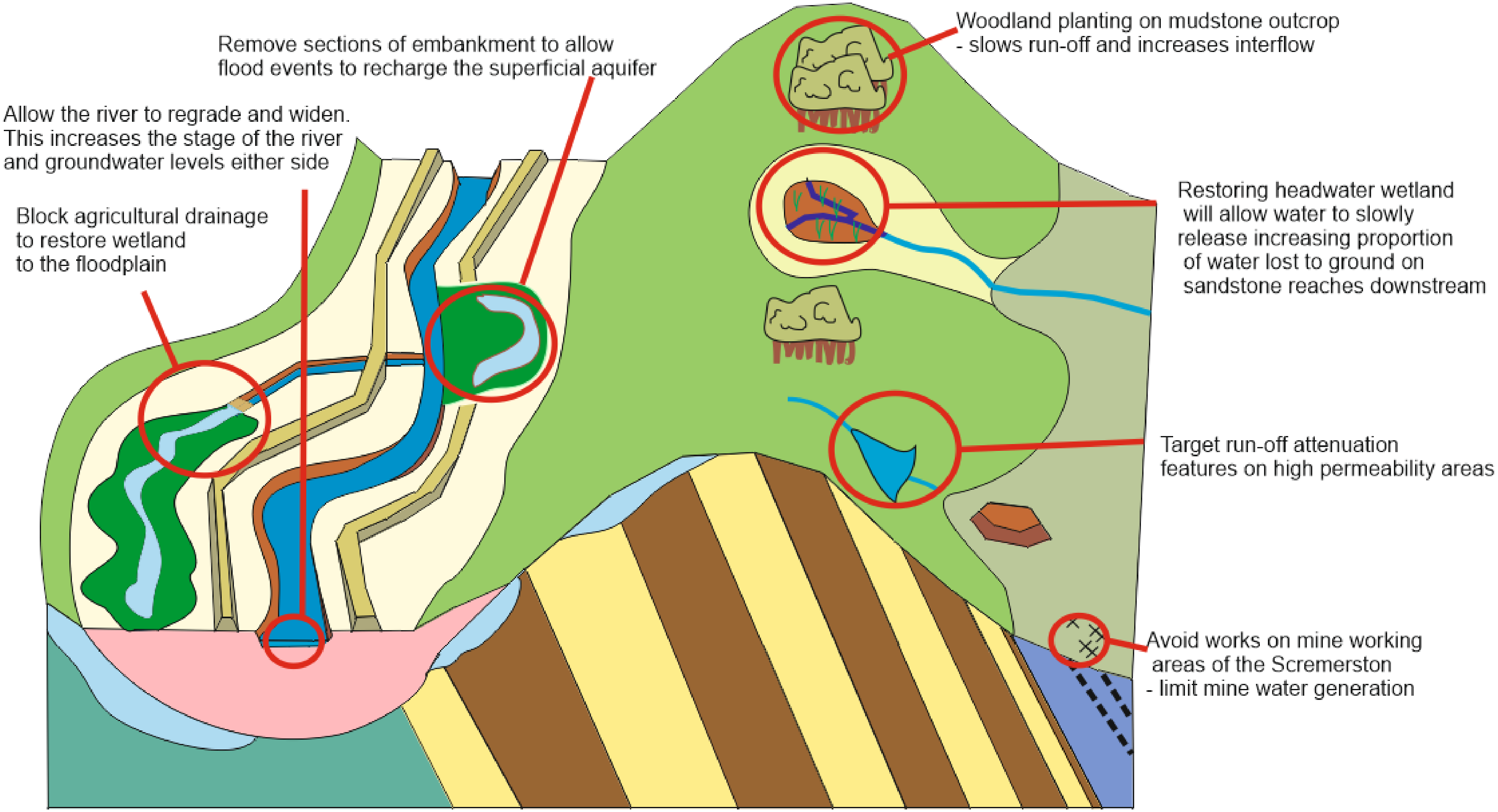


Figure 14-2: Till and Tweed AoI Conceptual Model with WWNP Measures

15 WWNP Potential Area Definition and Attribution

15.1 WWNP Feature Derivation

The following section outlines the process by which WWNP features were derived in GIS. These features are intended to be used as a screening tool to identify classes of potential WWNP which may be applicable across the middle/upper catchment, lower catchment or wider catchment where interventions are likely to differ in their functionality and interaction with groundwater processes as previously discussed in the generic conceptualisation section.

A national suite of WWNP features were previously generated across England as part of the Environment Agency's WWNP Evidence Base (2017[7]). These made use of national-scale fluvial and surface water flood risk as well as geology datasets to identify indicative measures, these were constrained to remove roads, railways, existing woodland, watercourses and urban areas. These WWNP features outlined in Table 15-1 formed the initial baseline for determining WWNP for this project.

Table 15-1: WWNP GIS datasets available within the Evidence Base

Evidence Base WWNP Dataset	Water Resources Potential
Floodplain Reconnection	Areas predicted at low risk within the Risk of Flooding from Rivers and Sea dataset which may indicate areas close to a watercourse that are poorly connected and may provide potential for floodplain reconnection to promote enhanced groundwater recharge.
Runoff Attenuation Features	Small areas of storage within the Risk of Flooding from Surface Water dataset which may indicate areas for enhanced storage to promote enhanced groundwater recharge.
Floodplain Tree Planting	Areas defined at risk from fluvial flooding which may indicate areas for floodplain reconnection, wetland development and low density planting and provide potential areas for enhanced groundwater recharge.
Riparian Tree Planting	Areas defined within a 50m buffer of watercourses which may indicate areas for river restoration and riparian planting and provide potential areas for enhanced groundwater recharge.
Wider Catchment Woodland	Areas defined over slowly permeable soils which may indicate areas for improved land cover management and provide potential areas for enhanced groundwater recharge. Note: the findings from this project have highlighted the need for any woodland planting to be carefully managed to avoid potential reductions in groundwater recharge such as with high density planting.

It was noted from stakeholder feedback that these national-scale interventions did not capture all potential areas and hence this project looked to further expand on the WWNP GIS provided with the Evidence Base as outlined within the following methodology.

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7 https://www.gov.uk/government/publications/working-with-natural-processes-to-reduce-flood-risk

15.1.1 Runoff Attenuation Features (WWNP_RAF)

These include local measures to intercept or divert water onto the floodplain and are most beneficial where the soils are permeable and there is an underlying aquifer. Strategies could involve large woody barriers, gully blocking, bunds and small-scale floodplain reconnection measures.

Features were delineated by:

1. Merging of both 3.33% Annual Exceedance Probability (AEP) and 1% AEP runoff attenuation features supplied in the Evidence Base.
2. Removing Source Protection Zone I and a 50m buffer around historic landfill and authorised waste sites, as these locations are not generally suitable for RAFs due to contamination risk.

An example of this type of feature is illustrated in Figure 15-1.

15.1.2 Mid/Upper-Catchment Storage (WWNP_CS)

These include more extensive areas than runoff attenuation features where storage and attenuation of hillslope flow pathways are most beneficial over permeable soils and underlying aquifers. Strategies could involve large woody barriers, riparian planting and small/medium-scale river restoration measures.

Features were delineated by:

1. Utilising the 0.1% AEP Risk of Flooding from Surface Water where there is likely to be flow and/or ponding during extreme rainfall.
2. Erasing runoff attenuation feature (RAF) to avoid double counting with other WWNP measures and erasing Flood Zone 2 deemed to represent lower catchment conditions
3. Filtering out small features <50m^2 which would not provide significant storage.
4. Erasing Source Protection Zone I and 50m buffer of historic landfill and authorised waste sites, as these locations are not generally suitable for RAFs due to contamination risk.

An example of this type of feature is illustrated in Figure 15-1.

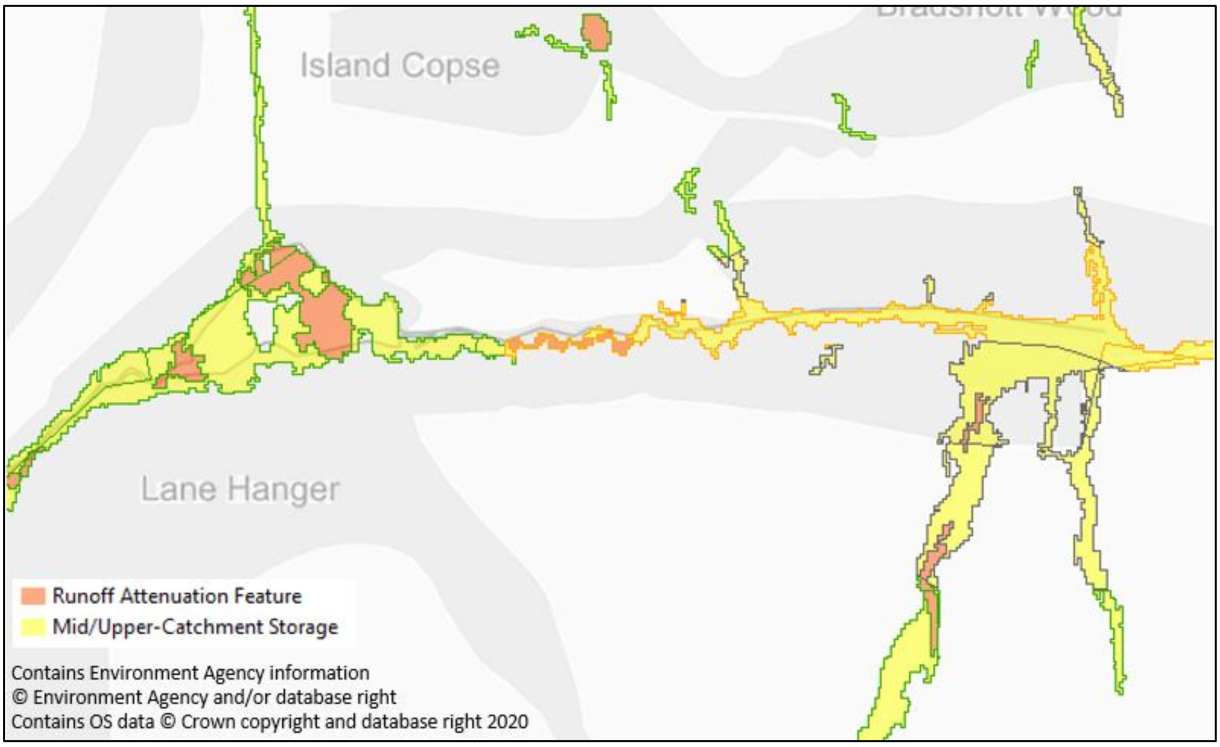

Figure 15-1: Runoff Attenuation Features and Mid/Upper-Catchment Storage

15.1.3 Mid/Upper-Catchment Riparian Zone (WWNP_RZ)

These include measures to intercept or attenuate minor watercourse corridors above the floodplain, particularly where the soils are permeable and there is underlying aquifer. Strategies could involve large woody barriers, riparian planting, rewilding and small/medium-scale river restoration measures. Features have been excluded within urban areas although it is important to consider the impacts of any features on isolated properties, undertaking additional exclusion or appropriately managing potential impacts based on local knowledge.

Features were delineated by:

1. Utilising the ‘riparian tree planting’ features supplied in the Evidence Base
2. Removing Flood Zone 2, deemed to represent lower catchment conditions
3. Filtering out small features <50m^2
4. Removing Source Protection Zone I and 50m buffer of historic landfill and authorised waste sites

An example of this type of feature is illustrated in Figure 15-2.

15.1.4 Lower Catchment Floodplain Reconnection (WWNP_FROP)

These include measures to intercept or divert water onto the floodplain in areas deemed at a national-scale to have a lower watercourse connectivity and associated flood risk and are most beneficial where the soils are permeable and there is underlying aquifer. Elevated groundwater levels within the lower catchment may seasonally reduce recharge capabilities. Strategies could involve large woody barriers, floodplain reconnection, wetland and storage area development and medium-scale river restoration measures. Features have been excluded within urban areas although it is important to consider the impacts of any features on isolated properties, undertaking additional exclusion or appropriately managing potential impacts based on local knowledge.

Features were delineated by:

1. Utilising the 'floodplain reconnection' features supplied in the Evidence Base
2. Removing Source Protection Zone I and 50m buffer of historic landfill and authorised waste sites

An example of this type of feature is illustrated in Figure 15-2.

15.1.5 Lower Catchment Floodplain Zone (WWNP_FZ)

These include more extensive areas than floodplain reconnection measures within the wider floodplain and may be of seasonal benefit where sited over underlying aquifers. Elevated groundwater levels within the lower catchment may: seasonally reduce the amount of recharge the ground can accept, or in the case of fully saturated ground prevent recharge. Strategies could involve floodplain planting, wetland development and medium/large-scale river restoration measures. Features have been excluded within urban areas although it is important to consider the impacts of any features on isolated properties, undertaking additional exclusion or appropriately managing potential impacts based on local knowledge.

Features were delineated by:

1. Utilising the 'floodplain tree planting' features supplied in the Evidence Base
2. Removing the floodplain reconnection features supplied in the Evidence Base
3. Filtering out small features <$50m^2$
4. Erasing Source Protection Zone I and 50m buffer of historic landfill and authorised waste sites

An example of this type of feature is illustrated in Figure 15-2.

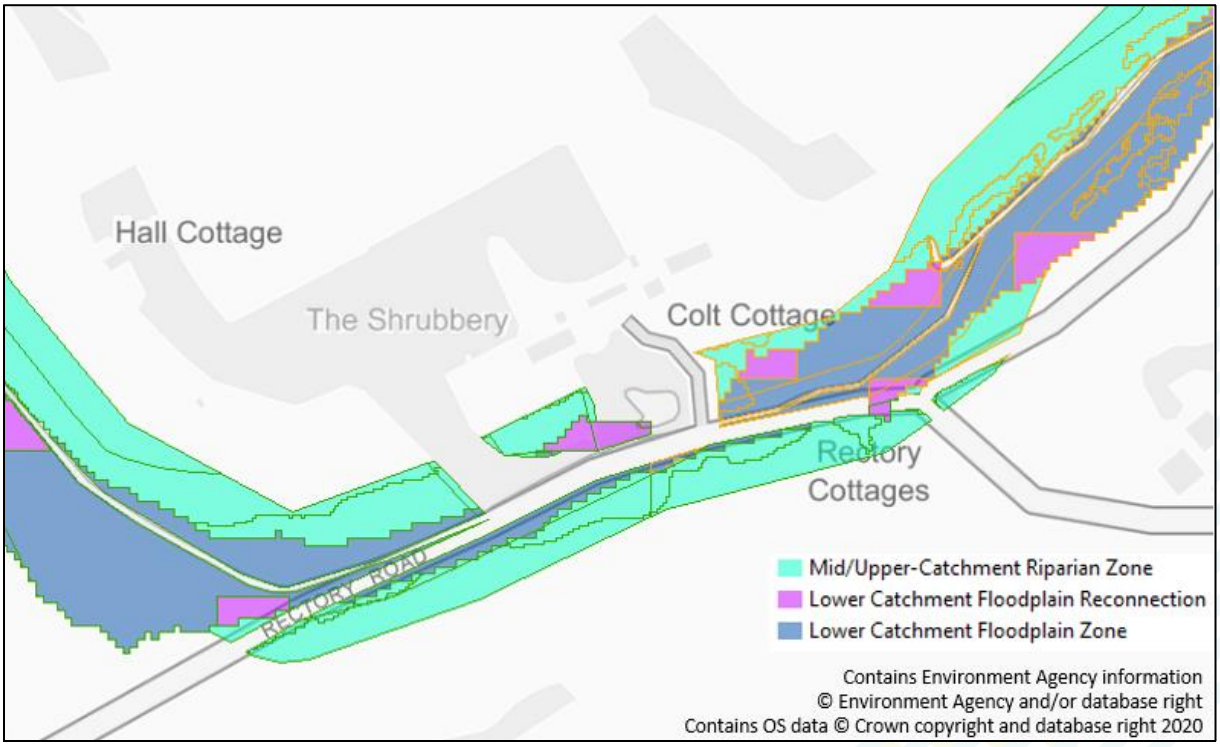

Figure 15-2: Mid/Upper Catchment Riparian Zone, Lower Catchment Floodplain Reconnection and Floodplain Zones

15.1.6 Slowly Permeable Soils (WWNP_SPS)

These include areas of impeded soil permeability and superficial till cover where land cover management strategies may include improving soils, de-compacting, crop cover and type management and planting of less dense woodland such as shelterbelts or wood pasture to increase infiltration rates. High density woodland should be avoided.

Features were delineated by:

1 Utilising the 'floodplain tree planting' features supplied in the Evidence Base
2 Erasing Source Protection Zone I and 50m buffer of historic landfill and authorised waste sites

An example of this type of feature is illustrated in Figure 15-3.

15.1.7 Arable & Grassland Land Cover Management (WWNP_LCM)

These include more extensive areas than slowly permeable soils defining areas of arable or grassland where land cover management strategies may include de-compacting soils, crop cover and type management and planting of less dense woodland such as shelterbelts or wood pasture to increase infiltration rates. High density woodland should be avoided.

Features were delineated by:

1 Merging Land Cover Map 2015 features of 'arable and horticulture', 'improved grassland', 'calcareous grassland' and 'acid grassland', this gives a data set covering most agricultural and non-developed land but excluding existing woodland.
2 Removing Source Protection Zone I and 50m buffer of historic landfill and authorised waste sites.

An example of this type of feature is illustrated in Figure 15-3.

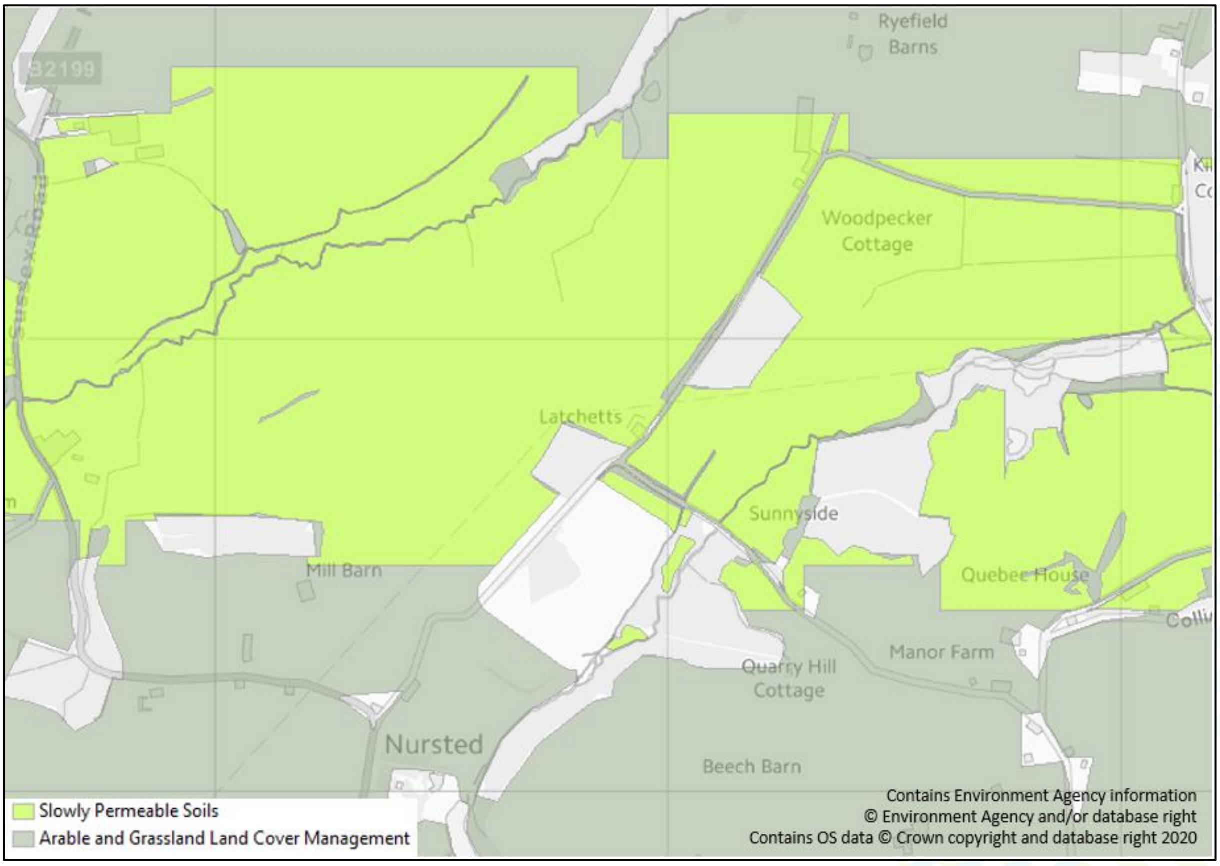

Figure 15-3: Slowly Permeable Soils and Arable and Grassland Land Cover Management

15.2 Wider Recharge Area Derivation

Given the primary aim of this project is to identify areas for improving water resources, there was a need to understand the overlying soils, superficial and bedrock aquifers, their characteristics and their associated recharge potential.

As identified within the data review, the existing Environment Agency groundwater vulnerability map[8] published in 2017 includes a wealth of information on the underlying geology that can be used to inform recharge potential. The individual datasets within the EA groundwater vulnerability map are combined via specific weightings as described within the vulnerability mapping methodology to give an overall groundwater vulnerability scoring. The dataset provides information at intervals of at least 1km^2 spacing and this is further split at the boundary of both superficial and bedrock geologies. It is appreciated that the BGS' Infiltration SUDS Map could also provide understanding to inform the potential recharge and considerations for enhanced infiltration WWNP interventions under an appropriate licence.

The following sections outline how the individual sources of data and the vulnerability scoring methodology within the Environment Agency groundwater vulnerability dataset was utilised and combined with others to develop wider recharge area GIS layers across each Area of Interest (AoI). These wider recharge area GIS layers are available as a project deliverable and have been discussed within each individual conceptual model report.

15.2.1 Wider Recharge Area Data Merging

The groundwater vulnerability map attributes below were combined with the following datasets which provided greater levels of aquifer and baseflow detail as well as soil information:

- Environment Agency Groundwater Vulnerability Map data sets used:
  - Drift patchiness/cover
  - Drift thickness
  - Superficial recharge potential/permeability
  - Bedrock flow type
- Environment Agency Aquifer Designation Map (Bedrock)
  - Aquifer designation
- Environment Agency Aquifer Designation Map (Superficial Deposits)
  - Aquifer designation
- 1km gridded BFIHOST data
  - BFI
- LandIS NATMAP Soilscapes data
  - Soil texture and drainage

15.2.2 Wider Recharge Area Scoring

Scores were associated with the dataset attributes as detailed in Table 15-2, with a lower score representing a greater benefit to recharge, dependent on whether it related to recharge of the bedrock or superficial aquifer. The attribute classes where common with the groundwater vulnerability dataset were maintained although the relevant superficial scores were modified from those applied within the groundwater vulnerability scoring system to

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8 https://www.gov.uk/government/publications/updated-groundwater-vulnerability-maps-improvements-to-methodology-and-data

account for the primary aim of understanding recharge potential rather than leeching potential.

Table 15-2: Wider Recharge Area Attribute Scoring

Attribute	Attribute Classes	Superficial Score	Bedrock Score
BFI The higher the value, the greater the inferred infiltration into both superficial and bedrock aquifer types	>70%	0	0
	≥40% and ≤70%	1	1
	<40%	2	2
Drift patchiness/cover The greater the cover, the greater recharge potential to superficial aquifers, although the greater barrier to bedrock aquifers. Areas with no designated superficial aquifer were deemed to expose bedrock aquifers for recharge and not be available for superficial recharge. Data based on BGS' GeoSure database.	<90%	2	0
	>90%	0	2
	No designated superficial aquifer	100 (Absent)	0
Drift thickness The greater the thickness, the greater storage potential to superficial aquifers although greater barrier to bedrock aquifers. Areas with no designated superficial aquifer were deemed to expose bedrock aquifers for recharge and not be available for superficial recharge. Data based on BGS' GeoSure database.	<3m	2	0
	3-10m	1	1
	>10m	0	2
	No designated superficial aquifer	100 (Absent)	0
Superficial recharge potential/permeability Recharge potential based on its primary and secondary constituents as defined by SNIFFER (2006[9]) Quaternary geology specialists.	High	0	0
	Medium	1	1
	Low	2	2
	No designated superficial aquifer	100 (Absent)	0
Bedrock flow Bedrock flow type through the unsaturated zone. Data based on BGS' GeoSure database.	Fractures well connected	N/a	0
	Fractures poorly connected	N/a	2
	Mixed	N/a	1
	Intergranular	N/a	2
Aquifer designation High aquifer storage size representing a greater recharge potential. Secondary (undifferentiated) includes superficial till deposits that were deemed to conservatively provide storage similar to Secondary A designations. Data based on EA designations.	Principal	0	0
	Secondary A, and Secondary (undifferentiated)	1	1
	Secondary B	2	2
	Unproductive/Absent	100	100

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9 SNIFFER (2006) Assessment techniques for Quaternary deposits in the UK, Part 2 Methodology and testing. Project WFD34. Report prepared by BGS for SNIFFER in June 2006.

The scores associated with each of the attributes in Table 15-2 were weighted as documented in Table 15-3 and grouped into classes after summing together as documented in Table 15-4. Weightings were qualitatively assessed based on their importance on recharge and water resources as discussed with hydrogeologist experts. Classification bands were determined based on analysis across a number of AoI to identify natural class breaks.

Table 15-3: Attribute Weightings

Attribute	Weighting Factor
BFI	x1
Drift patchiness/cover	x1
Drift thickness	x2
Superficial recharge potential/permeability	x3
Bedrock flow	x2
Aquifer designation	x2

Table 15-4: Superficial and Bedrock Recharge Potential Classes

Recharge Class (BR_Re/SF_Re)	Superficial Score Sum (post-weight) (SF_s)	Bedrock Score Sum (post-weight) (BR_s)
High	<7	<6
Medium	7-10	6-12
Low	>10	>12
Unproductive or Absent	Any instance of 100 (eg. where designated as unproductive or absent depending on superficial cover)	Any instance of 100 (eg. where designated as unproductive)

The LandIS NATMAP Soilscapes dataset of soil textures and drainage were used to infer soil permeability as classified in Table 15-5.

Table 15-5: LandIS NATMAP Soilscapes soil classes

Soil Drainage	Class (Soil_Perm)
Freely Draining	Very High
Slightly Impeded Drainage	High
Impeded Drainage (slowly permeable soils)/Variable	Medium
Naturally Wet/Surface Wetness/Blank (water)	Low

The supplied project GIS deliverables key attributes relating to recharge include:

- SF_s – superficial recharge score (post-weighting)
- BR_s – bedrock recharge score (post-weighting)
- SF_Re – superficial recharge class (High/Medium/Low/Unproductive/Absent)
- BR_Re – bedrock recharge class (High/Medium/Low/Unproductive)
- Max_Re – maximum recharge class between superficial and bedrock aquifers
- Soil_Perm – soil permeability class (Very High/High/Medium/Low).

15.3 WWNP Feature Attribution

After having developed the WWNP potential features outlined in Section 15.1 and wider recharge area datasets outlined in Section 15.2, each WWNP potential feature was attributed with its recharge potential. Given that WWNP interventions perform differently in their ability to affect recharge, it was decided to keep soils, superficial and bedrock recharge potential separate. However, a maximum recharge potential attribute (Max_Re) was defined based on the maximum recharge class between both superficial and bedrock aquifers for situations where a single recharge attribute is required for screening across both superficial and bedrock aquifers.

To provide further context to delineated WWNP features, a number of contextual datasets were attributed as summarised in Table 15-6.

Table 15-6: Additional attributes joined to WWNP features

Dataset	WWNP Attribute
BGS bedrock geology rock type	Bedrock
BGS superficial geology rock type	Superficials
JBA groundwater flood risk map depth range (1% AEP)	GWFM
CEH Land Cover Map 2015 land cover (based on the dominant land cover)	LCM2015
Natural England Agricultural Land Classification (2019)	ALC_Grade
Environment Agency source protection zones	SPZ
Environment Agency drinking water protection zones (groundwater)	DWPZ_SPZ
Natural England sites of special scientific interest	SSSI
Environment Agency groundwater dependent terrestrial ecosystems	GWDTE
Natural England special areas of conservation	SAC
Water Framework Directive Groundwater Waterbody Overall Class (cycle 2)	GW_WFD_OCLASS
Water Framework Directive Groundwater Waterbody Quantitative Class (cycle 2)	GW_WFD_QCLASS
Water Framework Directive Groundwater Waterbody Chemical Class (cycle 2)	GW_WFD_CCLASS
Water Framework Directive Surface Water Waterbody Overall Class (cycle 2)	SW_WFD_OCLASS
Water Framework Directive Surface Water Waterbody Ecological Class (cycle 2)	SW_WFD_ECLASS
Water Framework Directive Surface Water Waterbody Chemical Class (cycle 2)	SW_WFD_CCLASS

GWFM – the groundwater flood risk map is important to consider when identifying WWNP potential. This strategic dataset (outlined in Appendix B) highlights where there is a high potential groundwater flood risk that should be considered in conjunction with understanding of the groundwater system to ensure that groundwater flooding to receptors is not made worse. Where groundwater levels are predicted close to the surface (and this may be seasonal), this may reduce the recharge capabilities of surface storage potential. In areas where there is a regional groundwater model, more detailed site-specific mapping and modelling of depth to groundwater may be available.

ALC_Grade - the agricultural land classification provides contextual information on the underlying agricultural land productivity, ranging from Grade 1 (most productive) to Grade 5 (least productive), see Table 15-7. Siting WWNP features over more productive agricultural land needs to be balanced with the benefits of protecting the best and most versatile agricultural land. WWNP features situated over less productive agricultural land may indicate areas that are already seasonally flooded or of lower productivity.

Table 15-7: Agricultural Land Classification Grades

ALC Grade	Description
Grade 1 - excellent quality agricultural land	Land with no or very minor limitations to agricultural use. A very wide range of agricultural and horticultural crops can be grown and commonly includes top fruit, soft fruit, salad crops and winter harvested vegetables. Yields are high and less variable than on land of lower quality.
Grade 2 - very good quality agricultural land	Land with minor limitations which affect crop yield, cultivations or harvesting. A wide range of agricultural and horticultural crops can usually be grown but on some land in the grade there may be reduced flexibility due to difficulties with the production of the more demanding crops such as winter harvested vegetables and arable root crops. The level of yield is generally high but may be lower or more variable than Grade 1.
Grade 3 - good to moderate quality agricultural land	Land with moderate limitations which affect the choice of crops, timing and type of cultivation, harvesting or the level of yield. Where more demanding crops are grown, yields are generally lower or more variable than on land in Grades 1 and 2.
Grade 4 - poor quality agricultural land	Land with severe limitations which significantly restrict the range of crops and/or level of yields. It is mainly suited to grass with occasional arable crops (e.g. cereals and forage crops) the yields of which are variable. In moist climates, yields of grass may be moderate to high but there may be difficulties in utilisation. The grade also includes very droughty arable land.
Grade 5 - very poor quality agricultural land	Land with very severe limitations which restrict use to permanent pasture or rough grazing, except for occasional pioneer forage crops.
Urban	Built-up or 'hard' uses with relatively little potential for a return to agriculture including: housing, industry, commerce, education, transport, religious buildings, cemeteries. Also, hard-surfaced sports facilities, permanent caravan sites and vacant land; all types of derelict land, including mineral workings which are only likely to be reclaimed using derelict land grants.
Non-Agricultural	'Soft' uses where most of the land could be returned relatively easily to agriculture, including: golf courses, private parkland, public open spaces, sports fields, allotments and soft-surfaced areas on airports/ airfields. Also active mineral workings and refuse tips where restoration conditions to 'soft' after-uses may apply.
Source and further information: Agricultural Land Classification of England and Wales, Ministry of Agriculture, Fisheries and Food, 1988[10]	

10 http://publications.naturalengland.org.uk/publication/6257050620264448

SPZ/DWPZ_SPZ – the proximity to source protection zones and groundwater drinking water protection zones is an important consideration when identifying WWNP potential that may increase recharge into groundwater supplies. Areas of SPZ I have already been excluded from WWNP potential due to the strict regulation of activities within this zone. Features situated within other SPZ or DWPZ_SPZ should seek expert hydrogeological advice and following Environment Agency guidance[11].

SSSI/GWDTE/SAC – the proximity to sensitive environmental sites may highlight multiple benefit opportunities for WWNP although expert ecological/hydroecological advice should be sought to identify any impacts proposed WWNP measures may have on the locally specific ecosystem and its function.

GW_WFD/SW_WFD – the WFD groundwater and surface water classifications may also assist with screening WWNP measures to provide multiple ecosystem service benefits. Users are also recommended to review potential reasons for not reaching good WFD status and may find the included Nitrate Vulnerable Zones reference layer useful for where WWNP may provide water quality benefits on arable land cover.

11 https://www.gov.uk/government/publications/protect-groundwater-and-prevent-groundwater-pollution/protect-groundwater-and-prevent-groundwater-pollution

16 Summary and Recommendations

16.1 Summary

This project has aimed to investigate the potential for Working With Natural Processes (WWNP) to improve water resources, particularly those related to improving groundwater recharge. Whilst WWNP (alternatively known as natural flood management and nature-based solutions) have had a strong emphasis on understanding their potential for reducing flood risk, there has until now been little focus on their application to water resources. Integrated catchment management needs to consider the whole water-cycle including surface and sub-surface flows, with an understanding of soils and hydrogeology, to ensure the best trade-offs are made between the multiple benefits of WWNP.

As part of this project, a literature review has summarised research for a significant number of WWNP interventions and their potential interaction with groundwater resources.

The key messages include:

- Increased vegetation canopy size and root depth can reduce the proportion of water available for groundwater recharge.
- High vegetation planting density (such as dense woodland) can significantly reduce the water available for groundwater recharge, whereas lower density planting may be able to provide a greater balance between reducing flood risk and increasing water resources.
- Enhanced storage can provide opportunity for direct recharge where located over permeable geologies, however, even over reduced permeable geologies, it may still attenuate surface runoff permitting potential recharge further downstream within the system.
- The management of soils is key to reducing water losses (both evaporative or as surface runoff) and improving soil infiltration to permit greater groundwater recharge. There are a wide range of practices, particularly over arable and grassland, that could be integrated as WWNP to provide a water resource benefit over a significant area.
- WWNP interventions can respond quite differently and over differing timescales depending on their location, climate and underlying soils and geology. The transferability of research from one study to another area should be reviewed with significant caution.

A data review was completed to summarise key datasets that are relevant to: identifying potential WWNP; understanding the local context including groundwater processes and conditions; and identifying potential constraints which may limit the uptake or application of WWNP, particularly in relation to groundwater resources.

The characteristics of Areas of Interest (AoI) within ten Priority Catchments (PCs) were reviewed alongside local site visits and engagement with local groundwater specialists to develop conceptual models. These provided a range of geologies, land covers, land management practices, water demands, challenges and climates to review the potential for WWNP to improve water resources and maximise multiple benefits.

The project has highlighted the utility of dividing catchments into upper, middle and lower catchment sections when reviewing their potential to increase groundwater recharge based on underlying groundwater processes. WWNP sited within the upper catchment, where there is a greater surface to groundwater table depth, may be able to provide significant recharge potential over permeable geologies. The upper catchment also represents a significant proportion of a catchment over which land management has the potential to reduce surface runoff and improve recharge. The middle catchment is typically suited to slowing and attenuating surface flows that are generated to permit more gradual groundwater recharge when conditions permit. This may also include diverting flow pathways onto more permeable geologies where these vary. The lower catchment is typically an area of groundwater discharge where the groundwater table regularly or seasonally reaches the ground surface. Whilst this may seasonally reduce the potential for increasing groundwater recharge, WWNP can still provide potential to reconnect floodplains, raise incised water courses so increasing groundwater storage and improve surface water storage as well as provide significant multiple benefits including flood risk management, water quality improvements and improved biodiversity and habitats.

Based on the wider conceptual understanding, an approach to classify the superficial and bedrock aquifer recharge potential was developed and applied to each PC's AoI. This GIS deliverable provides an indicative review of the potential for recharge based on the baseflow, superficial and bedrock conditions across a spatial resolution of 1km^2 or finer. This dataset does not include representation of where groundwater levels are close to the surface, such as within the base of some valleys, which may limit the actual recharge potential.

A suite of WWNP interventions were expanded upon from those developed for the Environment Agency's Evidence Base released in 2017. These were classified into upper, middle, lower or wider catchment areas to link with the conceptual understanding. The WWNP interventions form a GIS deliverable and have been attributed with their recharge potential and potential groundwater flood risk. They have also been attributed with a suite of further information to provide wider context to inform their applicability, potential multiple benefits and consideration of a number of potential sensitivities. The features developed are intended to be used as a screening approach to identify applicable areas of the catchment for WWNP before local engagement can investigate specific WWNP interventions that would be most beneficial for both recharge and multiple benefits based on stakeholder requirements.

16.2 Recommendations

The following recommendations from this project are proposed.

Application of Project Deliverables

- Use conceptual models and GIS deliverables to screen areas within each AoI for prioritising areas of greatest potential recharge taking into account local groundwater processes and groundwater flooding. These could also be used cautiously to initially inform other areas of similar character to the AoI.
- Use WWNP GIS and matrix deliverables to identify potential intervention types most suited to a particular catchment interested in applying WWNP, taking into account their attributed recharge potential, underlying groundwater conditions and multiple benefits.
- Use suggested datasets reviewed here to provide further support and more detailed assessment for applying WWNP interventions. This includes recommendations to seek expert advice for assessing local flood risk, groundwater, ecological and hydroecological processes where the area may be sensitive to change.
- The GIS approaches developed in this project are scalable and could be used to inform national prioritisation of the more water-resource beneficial potential areas for WWNP. This may require further work on weighting the various layers, using Open Data to enable wider sharing or making allowances for different combinations of geologies and soils that were encountered in the ten PCs.

WWNP Research and Policy

- Provide a more holistic assessment of WWNP benefits to ensure their function for both flood risk and water resource benefit is considered and balanced. Significant momentum has been gained in the application of WWNP to manage flood risk including the release of £15 million for NFM schemes by Defra between 2016-2021. However, there is potential for certain interventions such as high density woodland to have negative impacts on water resources unless this is regularly considered through development of appropriate guidance and properly managed. It is recommended that these schemes which mandate monitoring consider how this can include an assessment of groundwater interactions and analysis across existing borehole networks.
- The upcoming Environmental Land Management Schemes comprising the Sustainable Farming Incentive, Local Nature Recovery and Landscape Recovery schemes provide potential opportunities to fund WWNP uptake.

Future Work

- Conduct pilot schemes with on-going monitoring to provide further evidence to support the uptake and financing of WWNP. It is particularly important that monitoring is installed ahead of any significant changes in land use so that the potential impact can be assessed over a sufficient timeframe and varying climatic conditions.
- Whilst this project has focused on WWNP as typically rural interventions, there is significant potential for SUDS within urban areas to have a role in capturing surface runoff and improving local water resources, providing any potential water quality issues are properly planned for and managed.
- Numerical modelling to investigate the potential recharge benefits of WWNP is currently being piloted across the Otter PC, investigating the potential change in recharge from improving soils, woodland planting and enhanced storage. It is recommended that these pilots are continued and expanded across different

geologies to develop an understanding of the seasonal and long-term benefit of WWNP to support and provide evidence for their wider adoption.

- Recently a new rainfall-runoff and water quality HYPE model was calibrated for England and used to assess the effectiveness of catchment sensitive farming measures. The published work[12] was used to inform the recent evaluation report[13], and the model has three conceptual soil layers using the same data that has informed the GIS analysis in this study. It has recently been improved to incorporate some of the key regional aquifers[14] that create surface-groundwater connectivity and can be used to quantify deep groundwater percolation and emergence. The model is driven by UKCP18 rainfall and temperature timeseries datasets, and it is possible to use it predictively to assess projected flows 2020-2040 and 2040-2080 and inform long term planning, essential for water resources. The model has been used experimentally to change soil properties for example organic soils / peat from good to poor condition to understand the changes in runoff responses to reflect improved land use management as a strategy for WWNP. Whilst not as detailed as a groundwater model, the HYPE model may provide a useful framework for quantifying the long term influence of WR beneficial WWNP measures.
- Similarly, the Environment Agency regional groundwater models could be used or adapted to test the impact of WWNP measures on groundwater levels and recharge in a range of climatic conditions. This would allow consideration of a range of WWNP change scenarios and how groundwater levels, recharge and WFD status of aquifers could be affected. It would be informative to investigate the potential variation in groundwater response to WWNP over a variety of geologies given the different hydrogeological processes and characteristics associated with each aquifer. It is recommended that new or future updates to regional groundwater models make consideration for their potential wider use and applicability for these types of assessment.

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12 Hankin, B.G., Johan Strömqvist, J., Burgess, C., Pers, C., Bielby, S., Revilla-Romero, B., Pope, L., 2019. A New National Water Quality Model to Evaluate the Effectiveness of Catchment Management Measures in England. Water 2019, 11(8), 1612; https://doi.org/10.3390/w11081612

13 Environment Agency (2019) Catchment Sensitive Farming Evaluation Report – Water Quality, Phases 1 to 4 (2006-2018). Natural England publication, June 2019. http://publications.naturalengland.org.uk/publication/4538826523672576

14 Wang, L., Stuart M.E., Lewis M.A., Warda R.S., Skirvin, D., Nadend, P.S., Collins, A.L., Ascott, M.J. 2016 The changing trend in nitrate concentrations in major aquifers due to historical nitrate loading from agricultural land across England and Wales from 1925 to 2150. Science of the Total Environment 542 (2016) 694–705

Appendices

A WWNP Matrix

B JBA Groundwater Flood Map

The JBA Groundwater Flood Map 5m Resolution v2.3 provides a rating of risk (on a scale from 0 to 4) from flooding during in a 1 in 100-year (or 1% AEP) groundwater flood event. The risk rating is based on the depth below surface at which groundwater levels would be expected to peak – this being estimated using a conceptual-analytical model of the groundwater system and varying spatially depending on local ground elevation, climatology and hydro-geological nature / thickness of the bedrock and overlying superficial deposits. The mapping is suitable for general broad-scale assessment of the groundwater flood hazard in an area but is not explicitly designed for the assessment of flood hazard at the scale of a single property.

As noted within this report and each Priority Catchment report, where groundwater levels are predicted close to or reaching the ground surface, there is likely to be a reduced potential for groundwater recharge during these times (which may be seasonal).

The table below summarises the risk levels predicted by the JBA Groundwater Flood Map.

Risk Level	Groundwater Flood Risk Indicator	Type of Groundwater Flooding Likely
4	Peak groundwater levels at or within 0.025m of the ground surface	1% or greater annual chance of groundwater flooding. The flooding in this zone will affect both surface and subsurface assets. Groundwater may discharge from the ground at significant rates and has the capacity to subsequently flow overland and/or pond within any local topographic hollows.
3	Peak groundwater levels between 0.025m and 0.5m below the ground surface	1% or greater annual chance of groundwater flooding affecting subsurface assets. Locally there is an additional possibility of groundwater welling-up at the surface.
2	Peak groundwater levels between 0.5m and 5m below the ground surface	1% or greater annual chance of groundwater flooding to deeper subsurface assets but near-surface manifestation of groundwater is less likely.
1	Peak groundwater levels are at least 5m below the ground surface	Very low annual probability of being affected by groundwater flooding.
0	Negligible risk	Negligible risk from groundwater flooding.

C Priority Catchment Conceptual Model Reports

D WWNP and Potential Area GIS Deliverables

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